Original Article

A complexity-based framework of financial risk assessment in large-scale projects

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Abstract This paper considers how complexity analysis can help determine financial risk exposure to large-scale projects. We propose that a treatment of risk as a complex, emergent phenomenon and employing network analysis offers a potentially rich framework for understanding risk exposure generally. The approach deals specifically with risk and its transmission mechanism which, we argue, finds a natural articulation in a network presentation. Our experimental results indicate that the potential for risk transmission is an emergent product of existing risk identification methods and the consequential designed, and also unplanned-for, risk management interventions. In developing our work, we show that areas of risk reception are more important for risk management than risk propagation; thus, leading to the conclusion that risk management in projects should prioritize protecting areas of vulnerability from risk impact as opposed to trying to disrupt the sources of risk to those vulnerable areas.
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Introduction

Large-scale projects involving, for example, infrastructure development, building construction, design of complicated products, new market and business ventures and so on, feature a wide array of risks, not only in terms of the scale of resources involved, but also with respect to the scope of interaction between potential risk areas that might otherwise be thought of as isolated or in some way immune to risk. Moreover, the number of partners typically involved in such projects and their different motivations complicates the picture further with business alliances, regulatory requirements and government agency needs all potentially impacting on project design, development, performance and outcomes. The challenge for project managers is acute in such circumstances with the prospect of project failure – to one degree or another – lurking unseen, and perhaps in an unknowable manner. All projects will have financial targets and related financial risk associated with them, if only because nearly all aspects of project failure will have a financial consequence. Thus, our particular focus is on financial risk and is motivated by the degree of attention paid to the area and to the inadequacies in risk assessment and management that we believe to be present. For example, existing approaches to financial risk assessment in large-scale projects provide only disconnected views of the potential for risk impact between various components of financial risk and other operating and external forces and do not, we argue, adequately capture financial risk interaction and possible risk transmission mechanisms. Even when the potential for interaction and transmission is appreciated, analytical methods conventionally used in financial risk assessment cannot recognize the nonlinearity underlying risk emergence and therefore cannot approach an understanding of the sources of risk and how remote areas of projects are potentially linked thereby limiting the perspective on the potential for interaction and transmission. And finally, we believe the extent of influence of a project's environment to be underestimated and that a more general problem of risk emergence through risk hierarchies to be an unrecognized feature of nearly every large-scale project.

In addressing these issues, we apply a network approach to modelling project financial risk that, we argue, provides insight into the nature of risk emergence in such complex environments. The next section details our introductory theoretical arguments, which illustrate a framework for understanding project constraints and how informal or unaccounted-for connections are a general and almost inevitable feature of all projects. We then present a formalization of how new risk types can emerge in project environments that feature unaccountable, informal constraints. Following that, we explain and develop a network approach to addressing risk that is generalizable in almost any direction and relies specifically on recognition of project environmental contexts as an important hierarchical feature that is largely underdeveloped in existing risk identification schemes. Our results also distinguish important attributes of risk transmission in terms of separately identifying risk impact from risk propagation and demonstrate that risk management should prioritize protecting areas of vulnerability from risk impact, specifically. Our final section concludes.

Complex Risk: Theoretical Structure

Constrained and unconstrained projects

In an earlier paper, Brookfield and Smith (2006) employ an approach to understanding the problem facing managers who desire to control the activities and projects they are responsible for. Ashby (1962) outlines how control might be conceptualized and which, as will be seen, is immediately generalizable.

Consider an element of a stylized project as represented in Figure 1. The project consists of two project resources E_1 and E_2, which are coordinated by an objective or task defined by management, M_i ($i = 1$, initially), otherwise known as a constraint. That is, the project is composed of resources that are operated on in some way and the operation is the task described by management. In practical and simplistic terms, E_1 could represent a subset of project resources that have to be combined in some way with a separate subset of project resources, E_2, to produce a particular outcome. In this context, M_1 could then represent the strategies or tasks to control these resources to meet managerial objectives. Specifically, this might be to avoid time and cost overruns. Although over-simplified and over-controlled, it is easy to see how a collection of resources and tasks could be built-up to represent an entire project. Once accepted as a valid description, it is not unlikely that such a conceptualization is easily extended into multiple and connected other activities that merge to form a project, or even to form a complete description of what an organization does. Technically, at a micro level, the components, E_1, E_2 and M_i, are arranged or coordinated to form a macro entity – defined as the project – which has an overarching purpose; for example, the completion of a building.

Figure 1 represents an idealized scheme of a fully constrained system whereby it is difficult to see how the task could not achieve its objective. It is unrealistic in practice, however, because fully constraining a project is unlikely to be feasible, which is why project descriptions are normally conceptualized at higher 'levels', offering lower resolution, because they are easier to plan for. Hence there is a natural limit to the degree to which a project could be constrained in the detail that would provide a fully constrained system because many of the activities surrounding resources are informal and/or unobservable. The outcome of recognizing limits to the extent to which management can

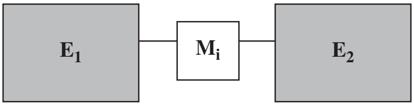

Figure 1: Formal project constraints. A project consists of two project resources E_1 and E_2 that are coordinated by an objective or task defined by management, M_i, otherwise known as a constraint. Management exercise control over resources by constraining their relationship with one another. A completely controlled project would be a fully constrained one.

fully or even comprehensively constrain a system is that other, informal and unplanned constraints emerge which reflect patterns of connection not anticipated at the outset or which cannot be resisted once a project begins. In an example of informal constraints, Hodgson (1997) explains the habits and rules that individuals employ to assist with task completion that would not be formally defined under M_i but nonetheless make more efficient and effective the achievement of organizational purpose. The idea that informal constraints emerge is most easily illustrated at the point of conjunction between human input and other project resources. Thus, if E_1 and E_2 are two individuals then M_i might represent a project relation between them, such as a reporting relation. Additional, informal constraints may arise as emergent behaviours, for example, from the very nature of systems and the purposeful nature of human systems in particular (see, for example, Jackson, 2003). For project risk management purposes, the informal constraints may lead to conditions that were clearly unintended by the designers of the project plan, or to by-pass controls that were perceived to be in place (Turner, 1976, 1978; Rasmussen, 1982; Perrow, 1984; Reason, 1990; Fortune and Peters, 1994, 1995; Tenner, 1996; Gladwell, 2000; Smith, 2000). Either way, informal relations are not defined by management, are hard to predict and, inevitably, are largely outside of their direct control. Such a situation is indicated in Figure 2 where emergent behaviour is denoted by the informal constraints, I_j. Thus, at any one point in time, management will not have 'control' over a significant number of risky operations (activities) that are taking place in a project but which are within the remit of their responsibility and, perhaps more significantly for risk identification, they may not even know that these operations (activities) are taking place.

Of particular interest are the direct linkages between M_i and I_j which are not indicated in Figure 2 but which are feasible. Thus, we expect that informal constraints not only to act directly on project resources but also to act directly on formal constraints. Once this is recognized, a new level and degree of project connectivity becomes possible and further constraints emerge which are at the same time semi-formal and semi-informal. This has been addressed in a more

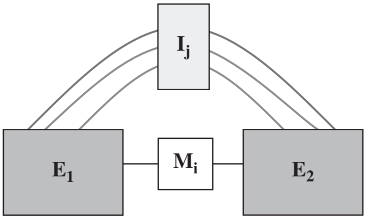

Figure 2: Informal constraints in a project. It is generally not possible to fully constrain a project. Informal constraints arise as emergent behaviours from the nature of systems and the purposeful nature of human systems.

general and analytically rigorous framework in Johnson (2006). In that paper, a distinction is drawn between order-1 and order-2 dynamics of systems. Order-1 dynamics are represented by functional changes, which are relatively easy to predict and manage. In a project finance (PF) context, this might relate to managing materials costs whereby costs are clearly seen to relate to material requirements of the project, competitive quotes for supply, quality variations and so on. Order-1 dynamics might therefore be reflected in increases in materials costs arising from higher materials consumption because of unplanned quality problems. The functional change in this instance is the relationship between materials consumption and quality: the lower the quality, the higher the materials consumption. Order-2 dynamics, on the other hand, are related to changes in structure and relations such as in the emergent I_j constraints in Figure 2 that show how the structure of a simple process can alter with additional connectivity. In this instance, it is unplanned-for connectivity that causes the problems and, in terms of risk management, it is anticipating this new connectivity that represents a challenge of a more significant degree than planning for variations around a known relationship.

Order-1 dynamics are defined in a way that only allows changes along pre-defined connections, or *formal constraints*. There might be some surprise, therefore, in terms of the level of materials costs but not in the relationship with quality and consumption. Order-2 dynamics represent changes in the structure of relations, such as new connections and new constraints that impact on quality and consumption in a way that is unexpected and give rise to costs that are unpredicted.

Informal constraints and emergent risk

Informal constraints cannot emerge from a fully constrained system (Ashby, *ibid*.); there has to be an element of an unconstrained project for informal constraints to intervene. One key way in which intervention arises is from what may be referred to as the project's environment. This may be economic, regulatory, weather-based and so on. At a lower system level, it might be competition for resources from within the organization responsible for managing the project.

The implications for project risk can be described generally before we demonstrate an example. In terms of Figure 2, it becomes clear that the object of managerial attention (E_1, E_2 and M_i) cannot be adequately addressed without recognition of the influence of I_j, which cannot be fully known at any point either at the project planning stage or during project execution. The implication is that inadequacy of managerial control may lead to elements of project failure, to one degree or other, which will come as a surprise (as it was not predicted) such that the situation may arise in which managers have to intervene in a failing project in which the control they actually have is considerably less than their perception of that control. The implications for risk management and the identification of what drives project risk are profound.

Our conceptualization of complex *emergent risk* may be formalized and which indicates its unpredictable nature.

Emergent risk may be explained in a more formal framework because of Baas and Emmeche (1997). Let $\{S_i^1\} i \in I$ be a set of risk factors and $Int^{t=1}$ represent interactions between these risk factors at time $t=1$. Interaction of risk factors at micro-level might be the result of external and internal events or conditions that may emerge unexpectedly. According to Sharit (2000), these events are 'either not perceptible or not comprehensible to the human controls and decision makers within the system' and qualify, in that sense, as an informal constraint. In order to understand the nature of informal constraints, we recognize the role of $Obs^{t=1}$ to represent a particular feature used in complexity science and elsewhere to denote a level of understanding of an entity that enables perception of phenomena when knowledge of a system's components, including that of the potential interactions, is not sufficient to reaching an understanding of system behaviour. We do not elaborate further and refer interested readers to Bass *et al*. Thus, the interaction and coupling at micro-levels can lead to the emergence of a new kind of risk system or structure at time $t=2$. The new risk system at observation $t=2$ could be represented as: $S_i^2 = R(S_i^1, Obs^1, Int^1)$ where S^2 is a new structure that now includes informal constraints which may manifest as new risk factors. This premise could lead to the notion that risk, R^2, is an emergent property and defined as: $R^2 \in Obs^2(S_i^2)$ and $R^2 \notin Obs^2(S_i^1)$. Fundamentally, R^2 is a product of the whole system in terms recognized as system effects on system entities (Lemke, 2000) and which reflect its self-organizing properties (Dempster, 1998; de Wolf and Holvoet, 2004).

Network Concepts and Statistics

Networks describe a set of relationships between entities. The entities in our study represent project contract elements, sources of risk and typical project cash flows. In network terms, all of these elements may be referred to as nodes and the relationships between the nodes are referred to as edges. A two-way relationship is known as an edge and a one-way relationship (such as an authority relationship) is known as a directed edge or arc. We employ both types of relationship in our study as we go on to explain. It is also possible to characterize the relationship further by weighting an edge or arc to reflect some attribute of the relationship such as intensity or importance. We do not do this have as our focus of attention is to establish a framework of analysis and establish what is possible rather than what is probable. In this case, all edge and arc weights are set to a value of 1.

The relationships between nodes may also be characterized by their distance. That is, how many edges/arcs are between two nodes. Thus, nodes may not have a direct connection but an indirect one. They may not have a connection at all. Of interest, therefore, is to have some idea within a network of distance between nodes from which we can then establish some measures of network average distance. This will be important because it allows researchers to establish a measure of connectivity and, in a risk context we represent below, connectivity is a key attribute of risk, specifically risk transmission. Thus, we can calculate the distance between any two nodes (where distance is the shortest path available) as the number of edges or arcs, and known as d_{ij} where i and j refer to the nodes of interest. It is also possible to calculate the average distance over the entire network, which is known as the characteristic path length, l, and is defined as:

$$l = \frac{1}{N(N-1)} \sum_{i \neq j} d_{ij} \tag{1}$$

where N represents the number of nodes in the network. Average distance in a project sense would provide information on the relatedness between project tasks. A short average distance measure would imply potentially quick risk transmission because the average route is small and therefore most project resources (nodes) and tasks (edges and arcs) are relatively closely connected. As a risk management exercise, therefore, protected areas should have sufficient distance between them in order to allow management the flexibility to respond should a risk event arise.

Another important attribute that we will employ and analyse is that of clustering. Clustering is a measure of groups within a network and it describes how concentrated or dense are the connections within the environment of a particular node. This environment is normally defined as being within one edge or arc of a particular node (known as a 1-neighborhood) or within two edges/arcs of a particular node (known as a 2-neighborhood). We use an environment of a 1-neighborhood cluster to characterize project risk clustering. Thus, the clustering measure is defined as the number of actual connections over a 1-neighborhood divided by the maximum number of possible connections. For node i, the clustering coefficient is defined as:

$$C_i = \frac{2n_i}{k_i(k_i - 1)} \tag{2}$$

where k_i are the 1-neighbours of node i. More generally and more importantly from a project risk point of view, network clustering measures can provide an indication of the connectedness of the network overall. Thus, the clustering coefficient for the entire network is defined as:

$$C = \frac{\sum_{i=1}^{N} C_i}{N} \tag{3}$$

In terms of answering the question 'is a network well connected?', or, 'is a network heavily clustered?', we employ clustering and distance measures from a random network as a benchmark. A random network is a network where the connections between nodes are randomly created and thus contain, by construction, no order or structure. A random graph is important because it enables researchers to establish the difference, based on certain network properties, between an observed (or structured) network and a random (or unstructured) network. Thus, we can measure both distance and clustering of a random graph and compare it with that obtained from a network representing project risk. We define below what might then be important values for distance and clustering measures and draw-out the implications from our results of understanding project risk.

PF Cash Flow Risk Network – Modelling and Concepts

Risk registers

PF risks are normally assessed with respect to all of the physical, technical, socio-economic and organizational aspects of the financed activity. The common practice is that risk registers are used as a tracking device to manage risk throughout the life cycle of a project. The purpose of a risk register is explained in HM Treasury green book (2004) as:

> A risk register lists all the identified risks and the results of their analysis and evaluation. Information on the status of the risk is also included. The risk register should be continuously updated and reviewed throughout the course of a project.

As a stylized example, Haskell (2007) has drawn-up the links between risk factors which are based on finance information extracted from a collection of past project contracts. These represent fairly standard elements and are derived and amended from standard PF contracts. This then allows generalizations, such as Haskell's, to have a fair element of relevance across a broad spectrum of project activities. Table 1 lists these risk factors in a risk matrix framework.

The conventional risk register as it relates to large-scale projects identifies environmental risks (identified as the columns in Table 1 and numbered 1–16). They represent sources of risk, which then impact on components of the project. These components are really subareas or financial clusters which the environmental sources will then influence. The financial clusters are identified by the numbers 17–48 and represent categorizations of areas of financial interest in typical large-scale projects. The remaining rows, identified by the numbers 49–65 are immediately recognizable as a conventional accounting cash flow statement, but with some headings that relate more directly to PF. Thus,

Table 1: Risk factors identified in a typical risk register

		Supply/traffic/ reserve	Market	Foreign exchange	Operating: technical	Operating: cost	Operating: management	Environmental	Infrastructure	*Force majeure*	Completion	Engineering	Political	Participant	Funding	Syndication	Legal
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
17	Concession								■		■		■				■
18	Govt. support			■					■								
19	Implementation agreement										■		■	■			■
20	Comfort letter (Govt.)												■				■
21	SPV/JVA				■	■	■				■		■	■			
22	Completion support									■			■				
23	LSTK EPC	■									■	■					
24	Performance bond										■						
25	Maintenance bond				■												
26	Insurance and LDs	■								■	■	■	■	■			
27	PPA/Sales contract		■	■		■								■			
28	Fuel supply agreement	■				■											
29	O&M agreement				■	■	■	■									
30	Environmental warranties							■									
31	Environmental permits							■						■			■

Table 1: Continued

32	Information memo		■									■	■	■		■	
33	Loan agreements									■	■				■	■	■
34	Political risk insurance												■				
35	Intercreditor agreement															■	■
36	FX hedging/swaps			■										■			
37	Offshore proceeds accounts			■									■				
38	Insurance report	■			■					■	■		■				
39	Traffic/reserves report	■															
40	Engineering report										■	■					
41	Environmental report							■									
42	Tax report												■		■		
43	Accounting report													■			
44	Mortgages/charges																■
45	Trustee agreements												■	■			
46	Cross charges		■			■							■	■			
47	Permitted charge												■	■			
48	Legal opinion							■					■				■
49	Quantity/service levels	■	■					■		■							
50	Price		■	■													
51	Revenue																

Table 1: Continued

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
52	Cash costs			■	■	■		■	■			■					
53	Variable operating expense			■	■	■		■	■			■					
54	Fixed operating expense			■	■	■	■	■	■			■					
55	Earnings																
56	Project loan			■											■	■	
57	Equity													■			
58	Total sources																
59	Capital expenditure	■		■							■	■					
60	Change in working capital		■			■											
61	Interest			■							■				■	■	
62	Cash taxes												■				
63	Principal repayment			■						■							
64	Total uses																
65	Net cash flows																

Columns 1–16 represent environmental sources of risk that impact on financial contract components in rows labelled 17–48. The financial consequences of the environmental risk sources are identified in rows 50–65. The typical risk register is an average representation of risk areas defined over a number of projects reported in Haskell (2007). Note that this table does not follow the convention adopted for subsequent tables in which directions of influence are read from *rows to columns*. The typical risk register reports risk sources as column headings and identifies risk impacts in rows.

areas of particular relevance to PF are project loan and capital expenditure and we would expect, in any practical application of the model, to see these areas generating particular activity. The risk register, presented in a block matrix form, then shows how the rows and columns are related by simply blocking the appropriate cell that relates a particular row with a particular column. At this stage, it is important to highlight two areas that we specifically address as failings of this type of approach. First, the direction of causality implied in the use of these registers is from column headings to rows. We would accept this view, and develop and elaborate it below. However, what is not specified in this presentation is any association or relationship or causality *between* rows or *between* column headings. We see this as an artificial separation, amend it, and explain why. Second, the risk register approach acts only as part of the appraisal documentation in the PF process. The approach does not allow or indicate how interaction and emergence between risk factors might the detected. The consequence is that the risk register illustrates associations between risk factors, only, and is therefore merely a description of potential risk areas.

Complex risk

Our chief criticism, therefore, of conventional PF risk matrix approaches is that they are not analytical and are unlikely, therefore, to provide any detailed guidance for problems outside of their framework or in areas where risk interaction is likely. They do indicate where initially effort might be concentrated and how to approximately price and allocate risk, but such traditional risk analysis methods are inadequate in highly complex and interconnected risks systems because dynamic and non-linear risk behaviour such as differentially influential interactions, a high number of interactions, nonlinearity, broken symmetry,[1] and nonholonomic constraints[2] cannot be addressed in a register.

Our hypothesis is that the interaction between risks factors is the driving force behind the emergence of PF risk and we would postulate, therefore, that the sort of complex interaction found in PF risk systems may be better investigated using network modelling techniques. At an introductory level, the type of complexity involved in terms of the range and interaction of the multifaceted factors that shape risks in a PF cash flow description is indicated in Figure 3.

Figure 3 shows a stylized PF financial risk system. In the model, nodes are used to represent risk factors and the lines (edges) represent various interactions and relationships between these risk factors. The system is split into three hierarchies with scope for interaction. The first hierarchy (H_1) represents the socio-political economic contexts (market risk, political risk and so on) that influence, and are possibly influenced by, risk factors at lower levels. The second hierarchy (H_2) represents the various clusters that describe components of different contract financial risks. The third hierarchy (H_3) represents the financial implications of the interactions from H_1 and H_2. The hierarchical structuring is important in understanding how risk interaction could take place

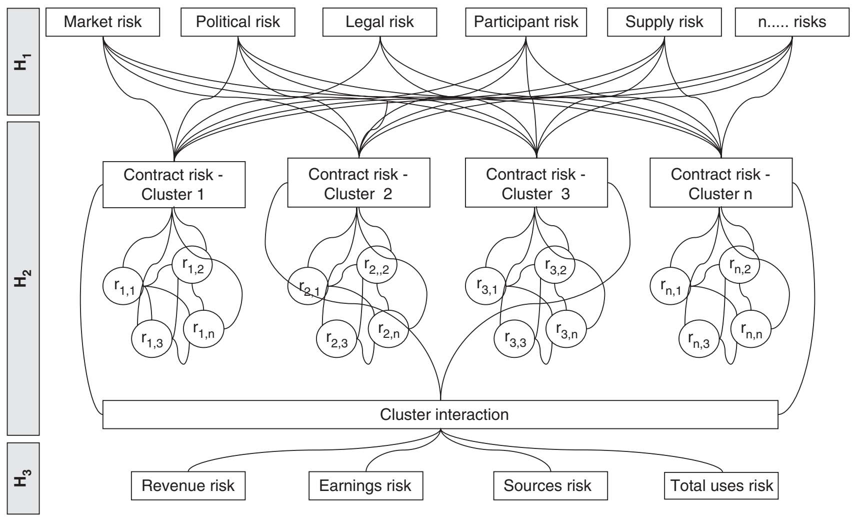

Figure 3: Heirarchical representation of project financial risk network. Nodes $r_{i,n}$ are used to represent risk factors and the lines between them represent various interactions and relationships between these risk factors. The system is split into three hierarchies with scope for interaction. H_1 represents the socio-political economic contexts. H_2 represents the various clusters that describe components of different contract financial risks. H_3 represents the financial implications of the interactions from H_1 and H_2 in terms of reported cash flow statements.

and represents a hypothesis of how risk in a typical PF contract may be understood. Interaction may be by association or by direct influence. If the direction of influence is one-way (from environment to project, for example) then the edges would be arcs and we would have a system of downward causation. This would be fairly typical as, for example, it is hard to conceive of many examples where projects have altered or influenced legislation or a regulatory framework. Nevertheless, feedback, which this would indicate, is a rich source of connectivity in many practical networks. In this introductory paper we do not use feedback loops to the environmental context, but try to illustrate how the environment can create connectivity within a project that alters a network's structural properties and thereby its exposure to PF financial risk. If the direction of influence is two-way, then we have an association between two risk elements without a defined dominance in any aspect of the relationship.

We only indicate an element of cluster interaction in the diagram at level H_2 without specifying its dynamic nature. The dynamic nature of cluster interaction, at a practical level, can be tested by comparative statics, and for which we develop an example. The interaction is a dynamic feature of the network we do not model specifically but which is important in understanding the process of risk creation. Instead, we provide a snapshot from one hierarchical

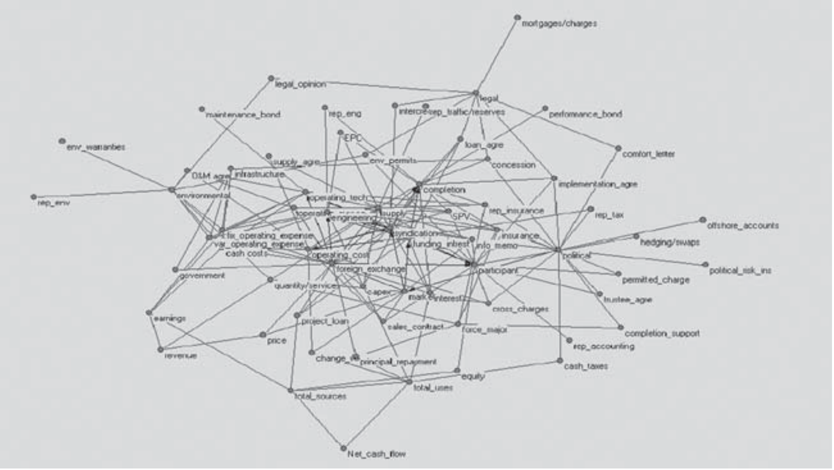

Figure 4: Network representation for PF_0: networks can be represented as block matrices or as a connected graph. The representation here indicates some degree of clustering for certain nodes.

PF risk structure to another. In this way, instead of modelling the risk process explicitly, we conjecture about some of the risk processes that could have generated two, related system states. Thus, we bypass the problem of specifying a dynamic, interaction process and allow the system endpoints to set putative boundaries to our considerations of what dynamics may link the two.

Thus, we offer two systems that represent, in a network fashion, Figure 3 at two points in time.

Figure 4 provides a representation at time 0 of Figure 3 (denoted PF_0) and Figure 5 provides a representation at time 1. Because the risk register does not recognize any connection *within* H_1, we populate both PF_0 and PF_1 with a number of detailed connections to redress this. First, we explicitly recognize the impact of political activity on market risk such as nationalization, currency inconvertibility, regulatory and tax risks that provide the backdrop against which market activities are conducted and market risks are either mitigated or exacerbated. Second, market risks are related to foreign exchange risks, clearly in relation to currency inconvertibility (via the political risk referred to), and also to foreign exchange exposure. Specifically, unmatched currency cash flows are potentially a feature of large, internationally sourced projects when uncertain project revenues (market risk) do not meet requirements of currency-based funding.[3] Third, market and foreign exchange risks are then connected to funding interest and syndication risks. Specifically, most bank funding for large-scale projects is funded on a floating rate basis which creates the potential for significant risk for participants. Co-financing by governments and

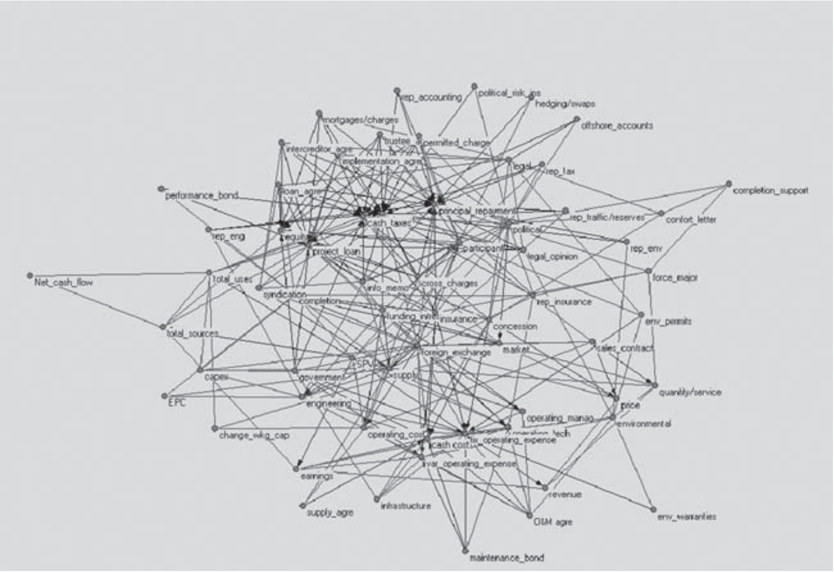

Figure 5: Complex network representation for PF_1: network representation for PF_1 (with block matrix counterpart reported as Table 5). The representation here indicates further clustering for certain nodes as a development from PF_0 but leaves the degree of sparseness largely unchanged.

other agencies would ameliorate this on a fixed interest basis but that will depend on the specific contract details.

Further edge connections are created in both PF_0 and PF_1 to create a richer structure of relations that relate H_1 directly to both H_2 and H_3: that is, environmental factors in H_1 are specifically connected to related areas of the contract financial elements (H_2) and to their financial expressions (in H_3). This is an attempt to mimic, more directly and in more detail, the environmental pressures that are recognized as an important feature of large-scale projects and which, in complexity terms, are referred to as downward causation. Additional connections created for PF_1 are designed to represent further connections that are likely to arise over time. Specifically, PF_1 reports a fuller set of links between components of PF contracts (at level H_2) to their direct financial consequences and impact on financial outcomes (at level H_3). The intention, here, is to represent emerging financial links of *within-project* risks that arise in period 1 as a consequence of environment pressures encountered in period 0. This could be argued to represent the informal constraint development outlined earlier. Thus, the network has been enhanced by the creation of a variety of arcs from nodes 17–46 (the key contract elements) to the nodes 50 and onwards and which describe, in a direct manner, the financial influence (risk) of contract elements to project financial outcomes.[4]

Results

Average distance and cluster analysis

The purpose of average distance and cluster analysis is to evidence network structural properties in order to see if important differences emerge in these properties as more realistic connectivity is introduced. Specifically, we compare the networks used to illustrate changed risk connectivity between PF_0 and PF_1 to those of the counterpart random graphs. Random graphs contain the same number of nodes and edges but where the connections between nodes are randomly generated. We create random graphs counterparts for each of PF_0 and PF_1. The counterpart random graphs then act as benchmarks from which we can observe the structural differences in networks that are hypothesized to represent PF risk structures. This allows us to see departures from randomness and to observe what structure the networks have. In particular, we look to see what level of connectivity and what type of connectivity enables us to discern small-world network properties in PF_0 and PF_1 that are likely to produce network features of interest in financial project risk assessment and then compare them to their random counterparts, and also to see the differences between PF_0 and PF_1 that would allow us to conjecture over the dynamics that might produce their differences. Small world networks exhibit features that we hypothesize reflect the properties of relatively easy risk transmission through risk areas: specifically, properties of high clustering (that is related risk areas) and low average distance between nodes (that is, connectivity 'times' are potentially low). Thus, in comparison with random graphs we should observe $C_{PF} \gg C_{Random}$ and $l_{PF} \approx l_{Random}$ for PF networks with small world properties.

Thus, we calculate distance and cluster indices for each of the graphs presented; that is, the risk register, PF_0 and PF_1. The results are presented in Table 2.

The risk register has virtually no clustering and is only sparsely populated in terms of its recognized connections between possible risk nodes. In fact, the degree of clustering is less than that of a random network of identical size in terms of both nodes and edges. This may, in fact, be a deliberate feature of a fully constrained project but that is not the purpose of a risk register. Registers are not constraint devices but are risk recognition devices that then enable project risk management constraints to be designed and implemented. This is our principal research point: because risk registers do not reflect risk management, it is in the creation of formal and informal constraints as a consequence of using the risk register as a risk recognition device that small world properties are created and hence risk exposure, we argue, is enhanced. With clustering less than that of a random network, risk registers appear to be working at system levels that feature few connections with the implication that random networks over-state the degree of interaction between nodes. To make this statement, however, risk managers must be able to say that risk areas are

Table 2: Cluster and distance measures

	Risk register		*PF_0*		*PF_1*	
	Model	*Random*	*Model*	*Random*	*Model*	*Random*
Cluster coefficient	0.0088	0.0398	0.1106	0.0441	0.1879	0.0634
Average distance	1.2832	4.6101	2.7774	4.2305	2.5629	3.0173

Cluster and average distance measures are reported for all networks. Cluster indices report the connectedness of nodes to nearest neighbours and proxy for the attraction of certain risks to other risks. Average distance estimates report the number of edges between nodes throughout the entire network and proxy network risk transmission potential. In all cases, cluster and average distance indices are benchmarked against equivalent but random networks to indicate departure from randomness.

isolatable and immune to potential change at the system level they are analysing. However, our view is that risk registers do not recognize adequately different system levels or their possible interaction; nor do they fully recognize the possibility for linkages within system levels. Thus, risk emergence, as we have explained it, is likely to take place across levels in a more fully connected manner than implied by risk registers. The implication is that risk registers are analytically flawed because they are too sparse in terms of their hierarchy connections. We have addressed this in our representations of risk in project networks in PF_0 and PF_1.

We have explained above the structural network differences between the risk register and PF_0 and PF_1, respectively. Generally, PF_0 recognizes hierarchical connections and PF_1 develops specific linkages between contract components and their financial outcomes. In PF_1, the average distance is of a similar order to the counterpart random network, and the difference between the network and their random counterparts is reduced as connectivity increases from PF_0 to PF_1. PF_1 thus exhibits distance that is recognizably close to that of a random network and, as distance reduces, so does the possibility that risk transmission has fewer nodes to connect in order to reach risk areas throughout the network. PF_1 is, also, recognizably distinct from a random network because of its clustering differences. Clustering has increased from PF_0 to PF_1 and is of an order of magnitude different to that of the counterpart random network. PF_1 thus more strongly recognizes the financial consequences of risk contract components than either the risk register or PF_0 do. This is not a significant increase in that PF_1 remains sparse. However, it is recognition of inevitable linkages given that contract elements in H_2 should ultimately bear a financial expression in H_3. Given the deeper hierarchical structural introduced in PF_0 and enhanced in PF_1 we see that downward causation has an important role to play in generating risk in PF contracts. Moreover, although both networks recognize the important role of environmental influences from H_1, it is PF_1 that specifies inevitable financial consequences which, because they are inevitable, are unlikely to be subject to managerial intervention. That is, once contract components are written in H_2, their financial consequences are likely to emerge in H_3 as the financial expression of the contract clauses is unavoidable. Thus, emergent risk develops in a manner that is structurally related to contract design given an environmental context: that is, downward causation through PF contracts can lead to network properties that provide for the rapid transmission of risk. The specific emergent problem is that risk may have been identified, but that its speed of transmission may not have been. The value of flexibility in such a framework is reduced, therefore, and with it, risk is consequentially increased.

In- and out-degree distributions

The PF_0 and PF_1 networks were conceived by drawing arcs from risk source nodes to target risk nodes in Figure 3, hence the risk network can be described as a directed graph. In this way each risk node may be characterized by the number of outgoing edges (k_{out}) and the number of incoming edges (k_{in}). By analysing k_{out} and k_{in} we can determine how influential are certain nodes to being receptive to risk influences from other nodes and, also, which nodes are, in turn, the potential progenitors of risk. We can therefore compute the incoming and outgoing degree distribution for the PF networks. An additional purpose of this exercise is to check whether the PF networks exhibit scale-free network properties for risk reception (incoming) and risk propagation (outgoing), which we use to supplement the findings already established for the network structure as a whole. The analysis will indicate broad areas where risk control may be exercised. For this purpose we have computed the power-law degree distribution of incoming and outgoing links as shown in Figures 6 and 7, respectively. We do this only for PF_1. In these figures, the horizontal axis represents the outgoing and incoming links and the vertical axis corresponds to the cumulative probability distribution of the incoming and outgoing links. According to Barabasi (2007), this distribution follows a Poisson distribution for random graphs, but for real-world networks the outgoing and incoming degree distribution follows the power-law distribution defined by $p(k) \sim k^{-\gamma}$ where $p(k)$ is the probability that a node has k edges (Braha and Bar-Yam, 2004) and γ is the distribution exponent. For PF_1, the figures demonstrate that the outgoing and incoming degree distributions follow the power-law function with an exponent $\gamma = 2.84$ for incoming links and $\gamma = 1.84$ for outgoing links. This suggests that there are relatively few risk nodes in the risk network with many links (high clustering). The consequence of this is that risk nodes that have a large number of links increase their risk impact or connectivity faster than risk links with few links. This conclusion is based on the fact that

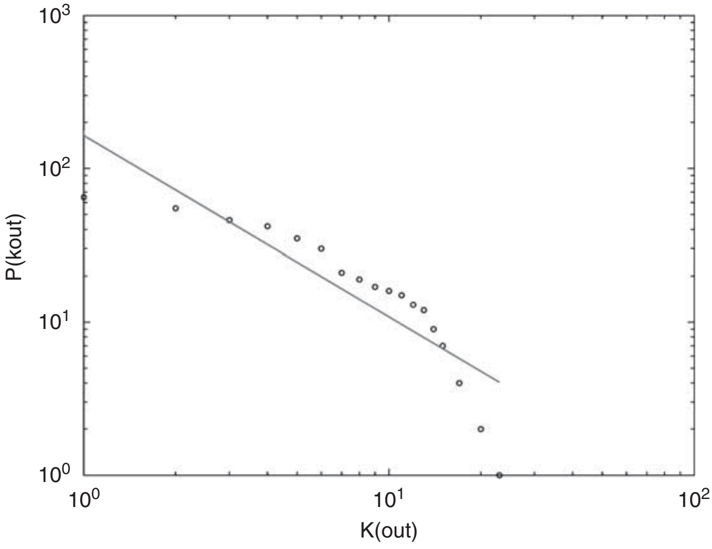

Figure 6: The log – log plot of the outgoing distribution of risk links. The horizontal axis represents the number outgoing links (k_{out}) plotted against the vertical axis which corresponds to the cumulative probability distribution of the related outgoing links arising, $P(k_{out})$. The outgoing degree distribution follows the power-law defined by $p(k) \sim k^{-\gamma}$ where $p(k)$ is the probability that a node has k edges and γ is the distribution exponent. The higher the value of γ the more likely is the node to have more outgoing links. γ is defined by the slope of the fitted straight line. A log – log plot is used to linearize the graph and is a standard format.

incoming nodes tend to connect to nodes with more links with higher probability (Barabasi, 2007). For risk management in PF networks, therefore, effort would be better concentrated on protecting nodes of susceptibility (potentially high risk reception) as PF contract design, as illustrated, appears to facilitate risk reception. Identification of vulnerable areas in terms of risk impact, therefore, should be assessed for their incoming degree.

Conclusion

What makes PF_0 and PF_1 more realistic to PF structures in practice is that project architecture is unlikely to be sparse, as in the risk register; it is likely to be impacted by environmental influences, thus enabling risk emergence within a hierarchy; and informal constraints are likely to arise and which add to, implicitly, the unpredictability of risk emergence. The fact that small world networks should arise in more realistic settings will not be a surprise, therefore.

Our principal research point was that, risk registers do not reflect risk management as it is in the creation of formal and informal constraints as a consequence of using the risk register as a risk recognition device that small world

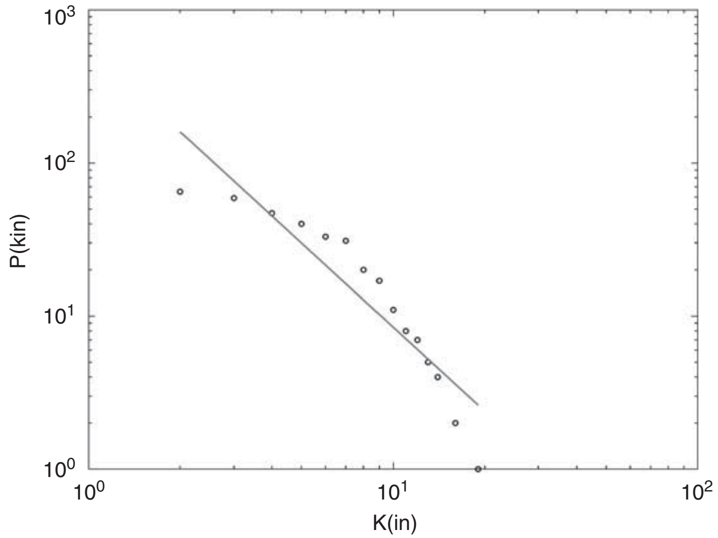

Figure 7: The log – log plot of the incoming distribution of risk links. The horizontal axis represents the number incoming links (k_{in}) plotted against the vertical axis which corresponds to the cumulative probability distribution of the related incoming links arising, $P(k_{in})$. The incoming degree distribution follows the power-law defined by $p(k) \sim k^{-\gamma}$ where $p(k)$ is the probability that a node has k edges and γ is the distribution exponent. The higher the value of γ the more likely is the node to have more incoming links. γ is defined by the slope of the fitted straight line. A log – log plot is used to linearize the graph and is a standard format.

properties are created and hence risk exposure is enhanced. Effective risk management in such circumstances will rely on risk managers recognizing the structural network properties they create from attempting to manage risk: that is, there is a second stage problem in which managerial intervention in a risk scenario through responding to the risks identified through a risk register (first stage) creates its own risks as a consequence of formal and informal constraints introduction (second stage). In this case, risk management takes on an iterative aspect. The fundamental danger for risk managers in this scenario is to ask the question whether risk intervention creates risk instability. Looking at isolated, unconnected risk areas cannot address this question because the answer rests on the structural properties of the risk network that has been created. At a deeper level, the full extent of risk intervention may not be knowable *ex ante* because the responses to new risk factors are continuous and also that the reverberations of risk interventions may not converge. These are different research questions that will rely on specific risk contracts to be addressed beyond the general risk framework offered here.

Finally, we highlighted that managing areas of vulnerability in projects should prioritize activities and sensitivities surrounding risk reception rather than trying to halt risk propagation. Of course, the two are not unrelated in a connected network because a node that propagates risk will find a receptive node elsewhere in the network. Our point, however, is that reception and propagation follow power laws with different degree distributions and that it is likely that once a node becomes receptive to risk it is likely to become more so and to a greater degree than an equivalent scenario in relation to risk propagation. One additional feature that risk managers might consider, which we suggest but do not elaborate, is to investigate the robustness of nodes with high k_{in}. One method of testing network robustness that is being researched in non-engineered systems is in relation to re-wiring the genetic network of the bacterium *Escherichia coli* (reported in Bennet and Hasty, 2008). The network analogy to this paper is akin to random re-wiring of edges between nodes. In the *E. coli* example, it was found that small scale re-wiring did not impact the organism, unlike the example of the project networks illustrated in this paper. The reason reported for the difference between biological and engineered systems is that the latter are often designed to the point just above failure and, indeed, there are cost incentives why that should be so. Incorporating deliberate network redundancy might be one way forward for dealing with complex project financial risk.

Notes

1 The situation where an entity obeys conventional laws in many circumstances but not in others and where the exception produces meaningful or substantive differences. In essence, 'theories of heat or chaos or complexity or broken symmetry are …. fundamental, because the general principles of these theories do not depend on what kind of particles make up the systems to which they are applied' (Weinberg, 2002). Therefore, an appearance of broken symmetry emerges when such general principles are broken.

2 Nonholonomic constraints refer to systems where not all the parameters in a system are identified or identifiable. For example, the system might not be fully constrained, thus allowing for the possibility of emergent, informal constraints.

3 Transactions currency risk arises from a mis-timed transaction when, in the intervening period, currency rates move adversely. Hedging will underwrite some risk, but not all because hedge transactions themselves (for transactions risk) will, too, have only a limited contract-determined period when they can be effective.

4 We provide Pajek programmes which have produced the results reported here, the detailed block matrices of the connections referred to in PF_0 and PF_1 and the detailed results for validation purposes. These may be found at: http://www.liv.ac.uk/management/DavidBrookfield/Project-Risk/Data

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