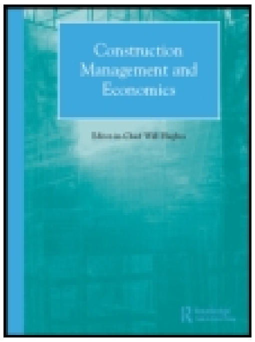

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Innovation management model: a tool for sustained implementation of product innovation into construction projects

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Technological advancement and demand for economic growth are driving product innovation in the construction industry. However there is concern that the industry lacks the mechanisms to effectively implement new products. Recent studies have developed a method for identifying and evaluating the risks which impact on new technology adoption and two constructs were generated for improving implementation rates. The aim is to investigate whether the constructs can be integrated to develop a practical tool for use by project stakeholders desirous to generate innovation. Process modelling, statistical analysis and failure mode and effect analysis are used to align the constructs into a test model (TM). Three rounds of Delphi gain a consensus on the TM outputs and the results produce the innovation management model (IMM). The IMM is a simple process flowchart which establishes the prioritized sequence of stakeholder activities required to implement a new technology at key stages in the project process. The IMM has implications for selection of procurement methods and will instil confidence in stakeholders to adopt new technologies. Additionally it provides a risk-based approach for stakeholder competency mapping and for sustaining product innovation in construction projects.

Keywords: Failure mode and effect analysis, innovation constraints, product innovation, process management, stakeholder competency

Introduction

Innovation is an idea developed and commercially implemented into an institution, industry, business or project (Freeman, 1989; Rogers, 1995). In a dynamic economy the introduction of innovation has been recognized as being central to increased growth and productivity, as well as having social and competitive benefits (Sproull and Goodman, 1990; Schmidt, 1995; Seaden, 1996). Studies on innovation have been undertaken widely in various industries such as the car industry (Abernathy and Clark, 1985; Womack *et al*., 1990), business and management (Drucker, 1986), computer technology (Tushman and Anderson, 1986), photolithography and digital industries (Henderson and Clark, 1990; Rothwell, 1992), retail (Riddle, 2000).

Innovation in the construction industry also brings considerable benefits (Dodgson, 2000; Gann, 2000; Van der Panne *et al*., 2003; Manley *et al*., 2005; Aouad *et al*., 2010; Yu *et al*., 2012). However, unlike other industrial sectors construction has historically failed to generate and sustain economic growth through innovation. This is despite the industry having characteristics seen as favourable to innovation (Tatum, 1986). For this reason there has been a significant drive by government to encourage uptake of new technologies across public sector projects in an effort to generate the available benefits (Latham, 1994; Egan, 1998). This has created an industry in which clients are demanding more complex buildings with advanced levels of integrated technology which are not feasible with current construction technologies (Winch, 1998; Gann, 2000; Steele and Murray, 2004; Cooper *et al*., 2005). Designers seek to incorporate new products into designs to satisfy client expectations but are nervous about the implications for the project as well as their business (Emmitt, 2001).

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Buildings comprise components and systems which interact with each other. Introducing a new technology into a building will have reverberations throughout other systems which may often be difficult to identify and thus manage (Slaughter, 1998). The design and construction phases of a project have historically followed a sequential and separated relationship (Cooper *et al.*, 2005). By being isolated from each other the design and construction activities of a project play only a limited part in the other's phase. Studies contend that these divisions give rise to long project times, poor quality control and slow piecemeal innovation (Gann, 2000; Moore and Dainty, 2001; Lloyd-walker *et al.*, 2014). Kwakye (1997, p. 53) speaks of a 'lack of cross-fertilization of ideas' between construction projects in which processes can be wasteful and ultimately fail to pass on the benefits of innovation, from one project to the next (Kwakye, 1997).

Therefore new technologies incorporated into construction projects have a high propensity for failure and literature identifies many lost opportunities where technologies were introduced but poorly managed, thus not fully implemented to generate innovation (Rosenberg, 1982; King and Majchrzak, 1996; Dodgson, 2000; Van der Panne *et al.*, 2003; Glass *et al.*, 2008). For this reason construction innovation researchers contend that product innovation needs to be managed effectively within the construction project to mitigate this potential for failure. However, innovation, by virtue of its definition, is an iterative process and cannot be confined within the constraints of a sequential project process and herein lies the problem for the growth of innovation in the construction industry. In order to increase levels of innovation in the industry the process of innovation needs to be captured and delivered alongside the project management process in spite of the complexities and challenges this presents.

The study is a development from previous work (Murphy *et al.*, 2013) which produced two theoretical constructs to facilitate the successful implementation of new technology into a building. The aim is to determine whether and how these constructs can be aligned to produce a model which can be used by stakeholders in the construction industry. Thus a method to align these two constructs is proposed to produce an innovation management model which can be used by industry stakeholders to adopt and implement new technology into construction projects.

Literature

It was primarily economists who undertook early studies on innovation such as Schumpeter (1930s–40s) and Schmookler (1950s). Schumpeter described innovation as a historic and irreversible change in the way of doing things, the development of something new which renders previous solutions redundant (Schumpeter, 1947). The broad range of innovation definitions put forward since the 1930s all proposed the notion of something 'new', the implementation of which makes irrevocable changes to its environment (Urabe, 1988). Rothwell's definition of innovation was widely adopted by early investigators of innovation in construction as, 'the first use of an idea by a new unit of adoption' (Rothwell, 1976). The concept of first use was echoed in many early construction innovation studies (Laborde and Sanvido, 1994; Harkola and Greve, 1995; Slaughter, 2000). However continuous first use within an industry would invariably render the innovation (if it could still be termed so) defunct. In this study it is proposed that the first use of a new technology is defined as the first implementation of a new technology into a construction project.

Definition of innovation

The Oslo Manual classified innovation as being either technical (product innovation) or organizational (process innovation) (Organisation for Economic Co-operation and Development, 2005). Process innovation is the introduction of advanced management techniques (Abernathy and Utterback, 1978; Anderson and Manseau, 1999). Rosenberg (1982, p. 4) defined product innovation as one which 'results in a qualitatively superior product from a given amount of resources'. Product innovations advance standard practice and challenge the status quo of traditional methods which many construction stakeholders consider the norm (Nam and Tatum, 1989). Product innovation in construction is defined as a new design, technology, material or component that has economic, functional, or technological value to the context in which it is adopted (Nam and Tatum, 1989). Slaughter (2000, p. 2) defined a construction innovation as 'the actual use of a nontrivial change and improvement in a process, product or system that is novel to the institution developing the change'. A significant omission in this definition is the concept of associated risk which is a key attribute of innovation (Winch, 1998; Dodgson, 2000). More recently Ling (2003, p. 635) addressed the concept of risk in her definition of construction innovation as, 'a new idea that is implemented into a construction project with the intention of deriving additional benefits, although there might have been associated risks and uncertainties'. Buildings comprise systems which interact with each other as well as the environment. Therefore, introducing an innovation into such a context can have reverberations throughout the other systems which may often be difficult to trace (Slaughter, 1998). Similarly, because every project is unique it is difficult to apply an innovation which is specific to one building across to another. All this produces a significant degree of risk which can be difficult to anticipate (Pries and Janszen, 1995; Winch, 1998; Dodgson, 2000). Risk and liabilities are synonymous in the construction industry and it is because of the concern about potential liabilities that many clients and professionals insist on using proven technology (Emmitt, 2001).

Drivers for construction innovation

Drivers for innovation in construction include the demand-pull of user requirements which stretch the boundaries of these standard solutions such as the regulatory environment (Pries and Janszen, 1995); fiscal policy (Porter, 1980); environmental policy (Tatum, 1989; Toole, 1998; Winch, 1998; Salter and Gann, 2003); competition policy (Newton, 1999; Steele and Murray, 2004; Tatum, 1988, 1989) and trade and education policies (Dulaimi *et al.*, 2002). Additionally the introduction of new technologies puts pressure on the industry to generate innovation (Nam and Tatum, 1997; Mitropoulos and Tatum, 1999; Gann and Salter, 2000). This technology-push can come from contractors, suppliers and manufacturers within the construction industry (Von Hippel, 1988; Slaughter, 1998) but more commonly involves the adoption of new technologies from other industries (Pries and Janszen, 1995). Kamien and Schwartz (1975) proposed that innovation in construction derives from a perceived demand (demand-pull) which then influences the direction and rate of technological development (technology-push). It is this model which most closely defines the typical driving mechanism operating within the construction industry (Gann, 2000).

Innovation management

The management of innovation has been defined as the management of new ideas into good currency (Van der Ven, 1986), the idea being invention, the currency being innovation. To consider how innovation is to be managed it is necessary to understand how it is implemented (Caerteling *et al.*, 2006). Implementation is the journey of the innovation from inception, through manufacture, installation, commissioning and finally to evidence of clear business benefits (Voss, 1988). Currently the accepted means of implementing an innovation into construction projects relies largely on standard project management techniques (Bresnen and Marshall, 2001; Hartmann *et al.*, 2012). Project management relies largely on planning and control techniques to deliver the project essentials of time, cost and quality. However it has been identified that an over-reliance on strict project controls and evaluation methods around which project management operates often stifles innovation (Koskela and Vrijhoef, 2001).

Government reports in the 1990s (Latham, 1994; Egan, 1998) called for the adoption of process management techniques to deliver innovation, rather than traditional project management techniques. It was reasoned that since the construction industry is concerned with the design and development of a building product it should look to manufacturing for reference on how to manage the process (Dulaimi and Kumaraswamy, 2000; Cooper *et al.*, 2005). In a process-driven model the innovation is progressed based on the right conditions being delivered in a sequential fashion. This is at variance with a project-driven approach where the critical paths and rigid milestones dictate a locked system, with little or no flexibility for an innovation to be accommodated.

A new management approach must also possess a degree of flexibility to allow reiterations in the project process to facilitate new technology adoption and implementation (Dulaimi and Kumaraswamy, 2000; Keegan and Turner, 2002; Cooper *et al.*, 2005). Lampel (2001) argued that such flexibility further depends on the acquisition and development of core competencies amongst the stakeholders to support the innovation process (Edum-Fotwe and McCaffer, 2000; Dainty *et al.*, 2005). This is a significant development of the process management approach. Rather than merely adoption of a process management approach, in which the right conditions are required at the right time in a sequential fashion, it is proposed that a stakeholder competency-based approach is required in which successful delivery is incumbent on the right stakeholder competencies being in place at the appropriate stage of the management process. This study seeks to investigate whether those two approaches can be aligned to produce an integrated management method for use by industry professionals in the implementation of an innovation into a construction project.

Modelling construction innovation

The problem with existing implementation models in construction is that they often fail to be translated from theoretical constructs into a workable solution for the industry. Tatum developed a classification system to enable industry professionals to analyse and improve a construction technology, such as an exterior wall installation or alignment of mechanical equipment (Tatum, 1988). The components of the classification system included (1) material and equipment resources, (2) construction-applied resources, (3) construction processes and (4) project requirements and constraints. The first three components dealt with the technical independencies of a technology whilst the fourth component sought to address the issue of project constraints on a technology. However the constraints focused largely on issues of project objectives, regulatory requirements and external factors but did not seek to address the impact of stakeholder competency to manage a technology. Additionally, and more pertinently, whilst the study provided a systematic approach to analysing the implementation of a technology it did not purport to investigate innovative or untested technologies and the risks associated with these.

Slaughter (1998) reviewed the literature from a wide range of non-construction industries to produce five models of construction innovation. Based upon current management and economic theories of innovation the models were differentiated by their degree of change from current practice, and their links to other components and systems. The five models are incremental, modular, architectural, system, and radical innovations. As a categorization tool Slaughter's model facilitates companies in planning their implementation activities; however, similar to Tatum's classification system, it did not purport to influence and direct management activity during the project process. However, a later study proposed that the implementation of construction innovations could be managed through a cycle of stages and activities (Slaughter, 2000). The cycle of stages was (1) identification, (2) evaluation, (3) commitment, (4) detailed preparation, (5) actual use and (6) post-use evaluation. It was proposed that the stages could differ slightly when applied to specific innovations and depending on the type of innovation. The five types of innovation (incremental, architectural, modular, system and radical) would be matched to a company's existing resources and competencies and an overall strategy for the firm to implement the innovation could be developed. Whilst the study presented a multidimensional model for innovation implementation it was specific to the activities of organizations within the construction industry that influence the supply and installation of construction innovations such as manufacturers and suppliers. It did not seek to address implementation within a specific project comprising diverse stakeholders and the challenges of implementation such as fixed timescale and budget constraints.

Wix and Katranuschkov (2002) proposed that process models provide potentially valuable tools for industrial use by developing effective, easy-to-use collaborative working methods which can be adopted by project stakeholders. 'Conceptual information modelling' is a term used to describe the capturing of project data within building construction and has been used to advance the importance of process models for communicating new ideas and procedures within the construction industry. Conceptual information modelling, as a precursor to process modelling, has significant insights for the development of a communication tool for use in the construction industry. More recently Davenport (2013) suggested that once a process model has been developed for generating product innovation a project will naturally develop ongoing improvements in its own established processes. This confirms early insights into innovation modelling which identified that product innovations often lead to process improvements. However, process improvements are required to produce product innovation. Furthermore, it is often the resulting process which sustains the initial product innovation (Utterback and Abernathy, 1975).

In light of the rationale above a process model is considered the most appropriate method for introducing a new management tool for sustaining innovation. Murphy developed a method for evaluating innovation constraints associated with the failure of new technology adoption (Murphy *et al.*, 2011, 2013). The study identified that failure of stakeholder competencies was the primary cause of constraints and in most cases precipitated the abandonment of the technology adoption. The study produced two constructs which established the management activities and the competencies required to successfully adopt and implement a new technology to generate product innovation. However, like previous construction innovation research, the two constructs were largely theoretical. Whilst both constructs held important information about successful implementation of a new technology they did not constitute a workable tool for industry use. Therefore this study aims to develop a practical tool for the industry incorporating these two constructs. It adopts a process modelling approach to propose an innovation management model that can be used to effectively communicate the critical activities to project stakeholders.

Research method

A review of the literature identified a series of preliminary hypotheses, notably: the imperative for an investigation into the sustainable adoption and implementation of new technologies into buildings within construction projects; the requirement for an appropriate mechanism to manage the implementation process to successful commissioning thus fulfilling the definition of a product innovation; and, lastly, the identification of stakeholder competencies as a potential driver for a mechanism.

The study adopted two constructs from work by Murphy which established the management activities and competencies required to successfully adopt and implement new technology into construction projects (Murphy *et al.*, 2013) namely:

(1) Innovation management flowchart (IMF): a flowchart of the systematic management activities required to implement an innovation against the stages of the project process.
(2) Constraint classification matrix (CCM): a matrix which establishes the stakeholder competencies required to mitigate the ongoing constraints acting on the new technology in order to successfully deliver an innovation.

Whilst both constructs hold important information required to generate innovation it is not possible from evaluating one construct alone to determine whether they address the study hypotheses. That is, the IMF alone did not identify the criticality of the management activities that was required for the success of an innovation. Similarity, the CCM on its own did not identify the management activities which could mitigate the competency risk. Therefore as separate constructs their value for practical application into the industry is limited. It is therefore proposed to determine whether the constructs could be aligned into an integrated practical tool for generating innovation in an industrial context. A method using process modelling and statistical analysis was established to align the constructs. It comprised identification and extraction of the data from each construct. Statistical analysis was used to evaluate the potential for alignment of the two datasets and validated using expert assessment. A process template was developed which established a framework into which the validated data from the two constructs could be populated. The output of the integrated process was a test model.

The test model (TM) provided an early framework of a working model which could be used by industry stakeholders to adopt and implement a new technology. Its format was sequential, reflecting the project stages, and incorporated the key project stakeholders which are key attributes for an industrial-based tool. Additionally, the activities from the model could be extracted to facilitate the development of programming software to integrate the activity requirements of the innovation with the project management programme. The programme would then be used as part of risk management workshops to inform ongoing management of the project.

To seek a consensus of opinion of the model outputs the Delphi technique was adopted. Three rounds of Delphi-based surveys with 18 experts were utilized to gain a consensus on the TM and its further refinement. The result of the Delphi process was an innovation management model (IMM). The IMM established a systematic sequence of activities required to manage the effective implementation of a new technology into a construction project, using core stakeholder competencies, to sustain a product innovation. Prior to evaluating alignment methods it was necessary to understand how the individual theoretical constructs were generated in the existing literature.

Innovation management flowchart (IMF)

The IMF is a flowchart of the systematic management activities required to implement an innovation against the stages of the project process. From the literature a set of project stages were generated which aligned the traditional project process with the process of innovation. Whilst previous studies have been carried out to link procurement systems with successful innovation, there had been scant work done to map the procurement process with the innovation process (Caerteling *et al.*, 2006). A concept model which mapped traditional project stages with the process of innovation was aligned using two established areas of literature: (1) the Generic Design and Construction Process Protocol (Hughes, 1991; Cooper *et al.*, 1998, 2005); and (2) two models of innovation literature (Marquis, 1968; Slaughter, 2000) (Figure 1 and Table 1).

Case study data from 30 technologies adopted and implemented into construction projects was collected using interviews and project documentation. Criteria were based on a multilayered set of requirements, the primary being a new technology product sourced from within the construction industry which has been successfully adopted, implemented and commissioned into a new building in the UK within the last five years. Examples of such products included: Okalux, an innovative light-diffusing glazing system with insulatory properties and Xanadome, a lightweight enclosure system for use in disaster management situations. Interviews were carried out with 96 project stakeholders including clients, project managers from construction firms, designers and product suppliers. The objective was to identify evidence of stakeholder activity used to adopt and implement the technologies mapped against the concept model. This provided a chronological sequence of recorded events about the 'journey' of the technology from adoption to working integration into the completed building.

The resultant data was populated into a flowchart template in which the x-axis of the template represented the project stakeholders implicit in the implementation of an innovation and the y-axis of the template represented the generic project stages.

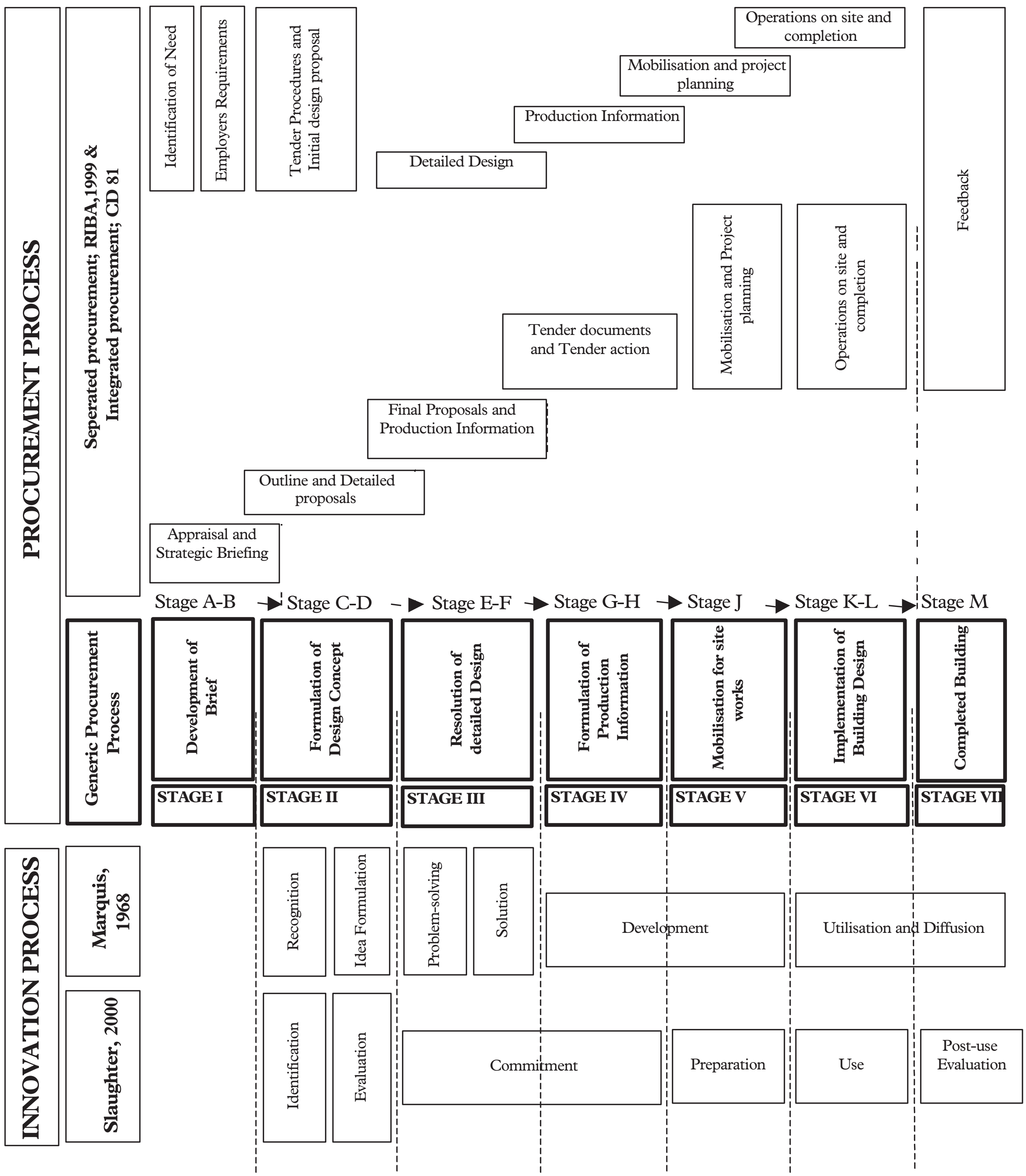

Figure 1 Concept model

The points at which the x-axis and y-axis intersected were populated with the stakeholder response activities required to manage the ongoing constraints on the technology.

Project stakeholders

Project stakeholders are the principal players in the adoption and implementation of a technology

Table 1 Concept model

Generic procurement stages		
Stage	Description	Definition
I	Intention to innovate	Initial feasibility study is carried out to assess options for delivery. A strategy will be put in place determined by the cultural buy-in to seeking out an innovative solution for the project
II	Formulation of design concept	Innovation is identified and defined, in response to the brief. Technical feasibility is assessed and a number of potential design solutions are proposed. Major design elements are identified and worked up to produce an agreed concept building design
III	Resolution of detailed design	Secure commitment for the innovation amongst stakeholders. Resources are committed to the design and intensive feasibility research is undertaken. (At this stage it is common for the innovation to be terminated or deferred.)
IV	Preparation of production information	Ensure the innovation is fully worked up, detailed and communicated to all potential stakeholders, in preparedness for construction. Commitment is secured through allocation of resources as well as the production of project documentation (drawings, specifications, etc.)
V	Preparation for implementation	Ensure engagement of the innovation to all relevant stakeholders, prior to commencement of the works. Preparation and development of the innovation may involve production of a prototype
VI	Implementation of the innovation	Install the innovation through onsite coordination, integration and feedback by all stakeholders. Whilst design uncertainties may have been reduced the risk of failure is greater at this stage. Adjustments and changes may be made on site to derive the most benefit from the innovation's implementation
VII	Post-implementation evaluation (completed project)	Handover of the completed building incorporating the innovation. The milestone initiates post-project review procedures to inform future work and exploit opportunities for the possible reuse of the innovation. *Post-use evaluation* will involve obtaining information about the innovation's implementation. This may be diffused to other teams, construction projects or design firms

(Manseau and Shields, 2005). They are also the project participants whose competency can adversely impact on the implementation process (Anderson and Manseau, 1999; Moore and Dainty, 2001; Dubois and Gadde, 2002; Miozzo and Dewick, 2002; Blayse and Manley, 2004). Adverse impact by stakeholders on the implementation of a new technology is usually largely non-intentional. In many cases the role of the stakeholder may form part of a series of passive events but their impact is often the key trigger that causes a constraint to occur (Miozzo and Dewick, 2002). The project stakeholders identified as implicit in the adoption and implementation of a technology are:

- Clients: the customers or receivers of services, financially responsible (but not otherwise liable) for the implementation of the innovation.
- Project managers: the persons with overall responsibility for planning and execution of the project, with team coordination responsibilities.
- Designers/Consultants: those whose intention it is to adopt the innovation, the creators and coordinators of the research required to oversee technical integration and communication of the innovation.
- Suppliers/Subcontractors: those who deliver the innovation, oversee the supply and installation, as well as the commissioning of the new technology. They may or may not be the inventors of the new technology.

For the purposes of this study the definition of 'innovation' is met when the new technology is fully functional in its context and producing the benefits anticipated. The supplier is a subcontractor and will require the services of the main contractor to implement the new product; however, the main contractor is not liable in the case of failed implementation.

Stakeholder competency

Any characteristic required for performing a given task successfully can be considered a competence (Wadalkar and Pimplikar, 2012). Stakeholder competencies are the combination of knowledge, skills and behaviours that contribute to personal effectiveness in a project (Edum-Fotwe and McCaffer, 2000; Lampel, 2001; Perera *et al.*, 2013). Each stakeholder is tasked with a role within which they must display the appropriate competencies to perform the job. Product innovations require operational competency such as communication, technical knowledge and personnel management (Egbu, 1999; Edum-Fotwe and McCaffer, 2000; Gann and Salter, 2000; Lampel, 2001; Dainty *et al.*, 2005; Gu and London, 2010). Organizational innovation requires strategic competency such as value, strategy and culture (Prahalad and Hamel, 1990; Javidan, 1998; Egbu, 1999; Edum-Fotwe and McCaffer, 2000; Gu and London, 2010; Lloyd-walker *et al.*, 2014).

It has been argued that innovation requires a great deal of flexibility within projects and that the effective management of such flexibility depends on the acquisition and development of competency in the personnel (Lampel, 2001). In the dynamic capabilities framework, Teece established the assumption that core competencies should be used to modify short-term competitive positions but can be used to build longer-term competitive advantage (Teece *et al.*, 1997). The right competency exhibited by key project stakeholders will support the core processes within the immediate project whilst establishing more effective competencies within the firms from which the stakeholders operate (Edum-Fotwe and McCaffer, 2000; Nahod *et al.*, 2013a, 2013b; Murphy, 2014).

In this study a stakeholder competency framework was established from the existing literature to develop the matrix. The McBer competency dictionary and codebook (Spencer and Spencer, 1993) provides a convenient scoring system against which behavioural responses can be awarded a numerical value depending upon the level of competency emerging from the behavioural event interviews. The stakeholder competency framework in this study was developed based on the established McBer competency assessment model (McClelland, 1973; Dainty *et al.*, 2005) in the following stages:

(1) Identification from case studies of the evidence of competency failure.
(2) Identification of the project stakeholders implicit in the competency failure.
(3) Data collection through interviews.
(4) Identification of management response activities used to mitigate the competency failure.

The management response activity data collected was used to develop a systematic sequence of activities. The sequence established the optimum process for implementing an innovation using the appropriate stakeholder competence. The findings were subject to validation and refinement using a panel of industry experts to produce a list of critical competencies required for the implementation of an innovation. The procedure is described below.

The initial stage was to identify poor stakeholder competency in projects seeking to implement an innovation. Using interviews and assessment of project documentation, 131 innovation constraints were extracted from 30 construction projects (Murphy *et al.*, 2011). Extraction of the constraints also involved identification of the competency failure which brought about the constraint and the project stakeholder implicit.

Project stakeholders are the key participants whose competence can adversely impact on the implementation of a construction innovation (Anderson and Manseau, 1999; Dubois and Gadde, 2002; Miozzo and Dewick, 2002; Blayse and Manley, 2004). Adverse impact is usually largely non-intentional. In many cases the role of the stakeholder may form part of a series of passive events but their impact is often the key trigger that causes a constraint to occur (Miozzo and Dewick, 2004). The project stakeholders identified as implicit in the management of an innovation are client, project manager, designer and supplier (Murphy *et al.*, 2011).

Each stakeholder was asked to describe a range of critical situations they had encountered in the project, what events led up to them (cause), who was involved (stakeholders), what did they consider the outcome might be if the situation continued unaddressed (effect). Furthermore the stakeholders were asked what they did to address the situation in order to mitigate the impending failure (management response activity). The interviews were transcribed and coded in accordance with the McBer Competency Dictionary and resultant data was subject to failure mode and effect analysis (FMEA). FMEA is a design risk assessment tool used to evaluate the *criticality* of potential risks. The extracted constraint data was subject to FMEA which identified the different risk rankings of the innovation constraints. The findings were subject to validation and refinement using expert consensus. It was found that eight key competencies were critically used by stakeholders to manage innovation. They comprised six operational competencies (Egbu, 1999; Edum-Fotwe and McCaffer, 2000; Gann and Salter, 2000; Lampel, 2001; Dainty *et al.*, 2005; Gu and London, 2010) and two strategic competencies (Prahalad and Hamel, 1990; Javidan, 1998; Egbu, 1999; Edum-Fotwe and McCaffer, 2000; Gu and London, 2010; Lloyd-walker *et al.*, 2014) (see Table 2).

Constraint classification matrix (CCM)

Rosenberg (1982) proposed that since most innovations turn out as failures more attention needs to be paid to the evaluation of innovation constraints. Constraints can produce a blockage in the overall project process

Table 2 Stakeholder competency framework

Operational competency	Description
Information and communication	Concerned with ensuring timely and appropriate generation, collection, dissemination, storage and ultimate disposal of information (explicit or tacit) as well as communicating effectively, listening sensitively and adapting communication to foster effective communication with other stakeholders.
Personnel management (human resources)	Involves the abilities required to make the most effective use of the people involved in the project to facilitate the successful implementation of the innovation.
Technical knowledge	Involves the abilities required to make effective analysis of technical problems arising from the integration of the innovation.
Planning and administration	Involves the abilities to identify relevant tasks to implement the innovation; how they can be done, allocating resources and monitoring progress.
Cost management	Involves the abilities required to ensure that the innovation is implemented within the approved budget; includes resource planning, cost estimating, cost budgeting and cost control.
Programme management	Involves the abilities required to achieve timely completion of the project and successful integration of the innovation; includes activity definition, sequencing, duration estimating, schedule development and schedule control.
Organizational competency	Description
Strategy and policy	Concerned with understanding the overall mission and values of the organization/client, adopting the innovation and ensuring stakeholder actions are aligned.
Culture and values	Involves the abilities to identify and propagate shared beliefs, values, and norms throughout the adopting organization/project.

and premature rejection of an innovation (Koskela and Vrijhoef, 2001; Hartmann, 2006). Constraints which act upon the project process are well documented in literature but those which act on an innovation are less well investigated (Eaton *et al*., 2006; Blismas and Wakefield, 2009). Studies have identified that prioritization of constraints is critical to any study on construction innovation particularly where there were numerous stakeholders involved within the project process (Eaton *et al*., 2006; Sebastian, 2011; Wagner *et al*., 2011). In the Murphy study the CCM is a matrix which establishes the stakeholder competencies required to mitigate the ongoing risk of constraints acting on a new technology in order to successfully deliver an innovation (Murphy *et al*., 2011).

A matrix is more often associated with concepts of linear algebra and mathematical theory. It is a tri-variable communication tool in which there are X and Y variables and where the two variables intersect there is a third variable, i.e. Z. This third variable is more often an empirical value which quantifies the relationship between the intersecting X and Y variables. In this study a matrix was formulated in which the x-axis represents the stakeholders and the project stages at which they were active and the y-axis represents the competencies of those stakeholders implicit in the implementation of the innovation. The Z variable in the matrix represents the constraint and associated risk value acting on the product and encountered by that stakeholder at that stage. To graphically represent the intersecting data the constraint risk values were displayed in the form of a bubble marker. The size of the bubble marker was scaled proportionately to the constraint risk: low constraint risk; medium constraint risk; high constraint risk; severe constraint risk. The resultant CCM is a collective series of bubble graphs (Figure 2).

Test model formulation

The two theoretical constructs separately provided important information; however, it was not possible from evaluating one construct alone to determine whether they addressed the study hypotheses, i.e. a mechanism to facilitate the sustained adoption and implementation of a new technology into a building to generate product innovation. Therefore it was proposed to determine whether the constructs could be aligned. The first stage was to confirm the compatibility of the two sets of source data.

Significance analysis

It was assumed that the source populations of the IMF and the CCM had normal distributions and equal variances; however, evidence of this significance was required before the two sets of data could be aligned. If the data did not evidence reasonable statistical

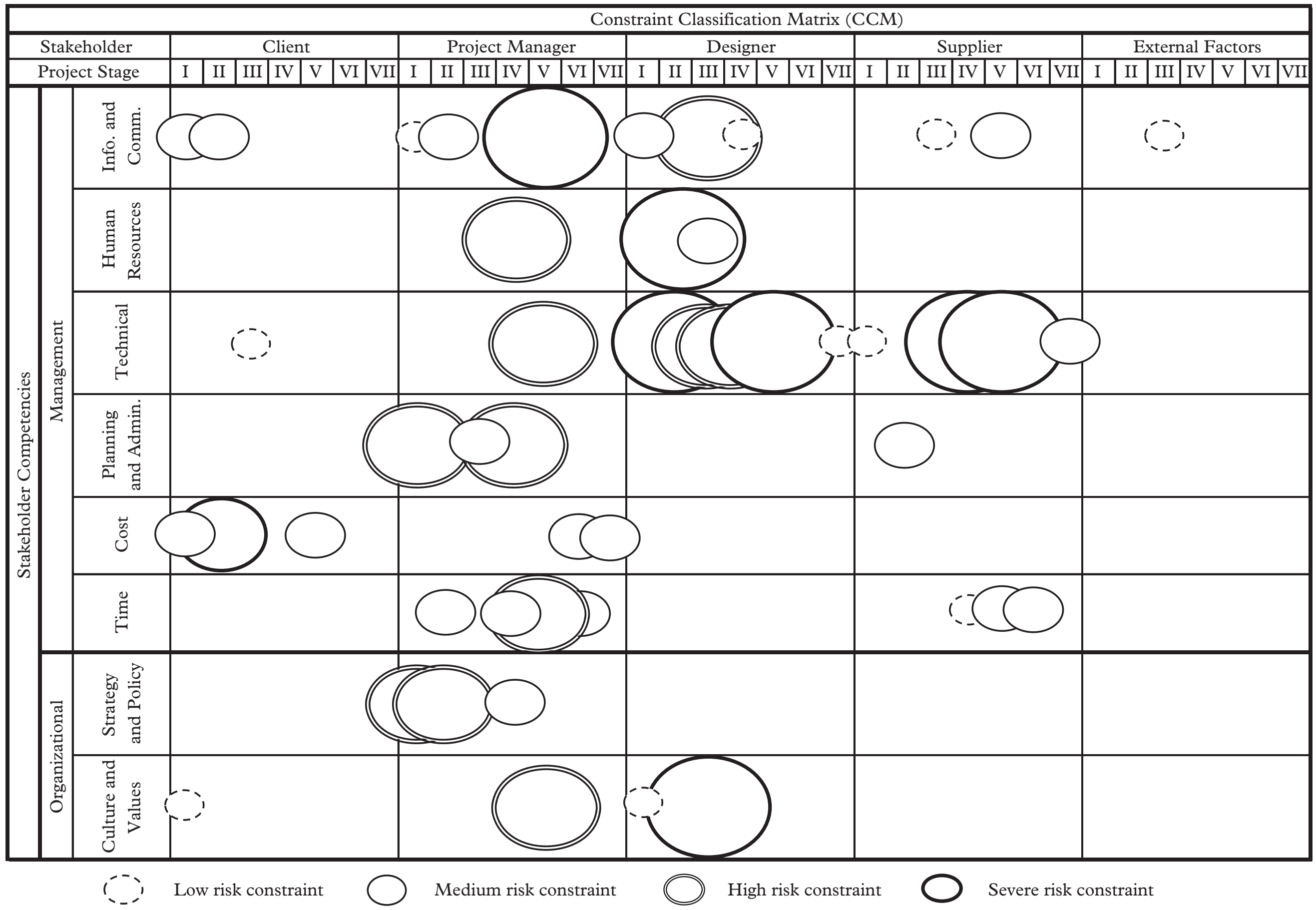

Figure 2 Constraint classification matrix (CCM)

significance the data outputs could not be combined and would need to be analysed separately.

A *t*-test was undertaken to compare the means of the two samples of data (Kinnear and Gray, 2004). The samples were dependent and paired in that the two constructs were matched by the particular variable, i.e. the risk priority number (RPN) of the constraints common to each dataset. The objective was to assess whether the difference between the sample averages was significant. Since the critical region of the sample was distributed symmetrically, it was intended to undertake a two-tailed test of the data. To check for anomalies in the data before running the *t*-test a scatter plot was constructed. The scatter plot indicated a clear positive relationship between the two sets of data when the two means were considered and provided a degree of confidence to proceed with the *t*-test. In preparing to test for significance it was necessary to define the size of the effect expected. Using findings from published literature the test was measured against a categorization of the effect sizes based on work by Cohen (1988).

The *t*-test was calculated by dividing the difference between the sample means by an estimate of the standard deviation of the distribution of differences. Since the sample variances have similar values it was intended to work with a pooled estimate of the supposedly constant population variance. The results of the first stage showed that the value of *t* (on 30 degrees of freedom) was 3.953, and that the p-value, sig. (two-tailed), was 0.0004. The result of the *t*-test was significant beyond the 5% level. The 95% confidence interval on the difference between the means was (15.16, 47.55), which excludes zero, the value under the null hypothesis. To obtain the effect size (Cohen, 1988) estimates of these population values were used, i.e. 31.35 for the difference between means and 44.161 for the standard deviation of the difference scores. From the Cohen's Table this indicated a medium effect. This evidenced that there was statistical significance between the two groups. However, since the result of the Cohen's test was 'medium', a Pearson correlation test was carried out and the results confirmed a correlation with the significance test.

The first output tabulated the means and standard deviation of the two variables. The second output tabulated the Pearson correlation with its p-value. With a value of 0.234 and a two-tailed p-value of 0.204, it could be concluded that the correlation coefficient was significant beyond the 1% level thus representing a 'medium' effect. Since the results of both groups were found to be significantly similar, it was therefore considered appropriate to align the two sets of data.

A process template was constructed to populate the data from the two theoretical constructs. The x-axis of the template represented the project stakeholders implicit in the implementation of an innovation. The y-axis of the template represented the generic process stages. The points at which the x-axis and y-axis intersected were populated with the management response activities required to manage the innovation constraint. However the risk criticality of each management activity was not evident from the process flowchart. For this reason the data was subject to FMEA.

Failure mode and effect analysis (FMEA)

FMEA is a charting technique for design risk assessment and originated in aeronautical and mechanical engineering before being applied in the construction industry (Andrey *et al*., 1998; Nielsen, 2002). It is considered an appropriate tool for this study in that it allows for subjective assessment of data to produce empirical values for statistical analysis. FMEA evaluates the criticality of potential causes and effects of product failure in a process or system. By identifying the risk of a constraint acting on the new technology the project manager can adapt the management strategy to facilitate the implementation of the new technology. An FMEA is calculated by multiplying the occurrence (O), severity (S) and detection values (D) of a potential risk occurring to the new technology. The values for O, S and D are produced through tacit assessment and judgement by stakeholders. The resultant value, the RPN, enables actions to be prioritized according to their potential risk.

FMEA produced risk rankings for each of the constraints identified in the CCM. The higher the RPN the more urgent was the action required. The lower the RPN less urgent *but still necessary* action was required. The results were fed back to the participating stakeholders for verification and the following data was tabulated:

(1) Innovation constraint
(2) Implicit project stakeholder
(3) Competency failure
(4) Process stage at which the constraint occurred
(5) Process stage at which the constraint impacted (had an effect) on the project
(6) Risk of occurrence of the constraint (O)
(7) Risk of severity of effect of the constraint (S)
(8) Probability of non-detection of the constraint (D)
(9) Risk priority number (RPN) of the constraint
(10) Management response activity to the constraint

A Schedule of Construct Data (SoCD) was developed of the above data. See Appendix 1. From the data the least constraint RPN value obtainable was '1', and the highest was '1000' (i.e. 10 10 10 = 1000). Hence, a resultant risk prioritization scale would be, '1' (*least constraint risk*) to '1000' (*highest constraint risk*) and could be subdivided (see Figure 3).

This enabled the resultant management response activities to be ranked in terms of the criticality in the process. The process template was populated with the data to produce a test model. The test model provided an early framework of what a practical model to manage innovation might look like. Its format was sequential and logical which are key attributes for an industrial-based tool (see Figure 4 parts A and B).

To develop and validate the test model a Delphi technique was utilized to secure a statistically significant consensus on the weighting of the risk rankings for each management activity from experts in the field. A statistically significant consensus on the risk rankings of the management activities was investigated to refine and validate the test model.

Expert evaluation

The Delphi technique is used in complex sectors in which a consensus is to be reached such as theory and design application (Corotis *et al*., 1981). The Delphi method is a highly formalized method of communication that is designed to extract the maximum amount of unbiased information from a panel of experts. The iterations of the Delphi exercise enabled the experts to modify their risk rankings and project them beyond their own opinions.

The Delphi study comprised three rounds of questionnaire responses. In the first round respondents were required to rate the activities of the TM, in terms of

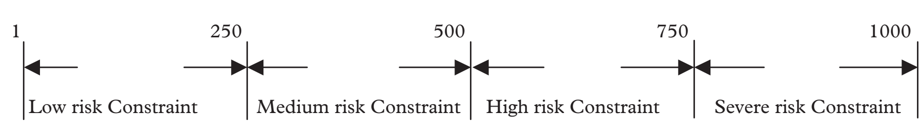

Figure 3 Constructing a scale of constraint criticality #1

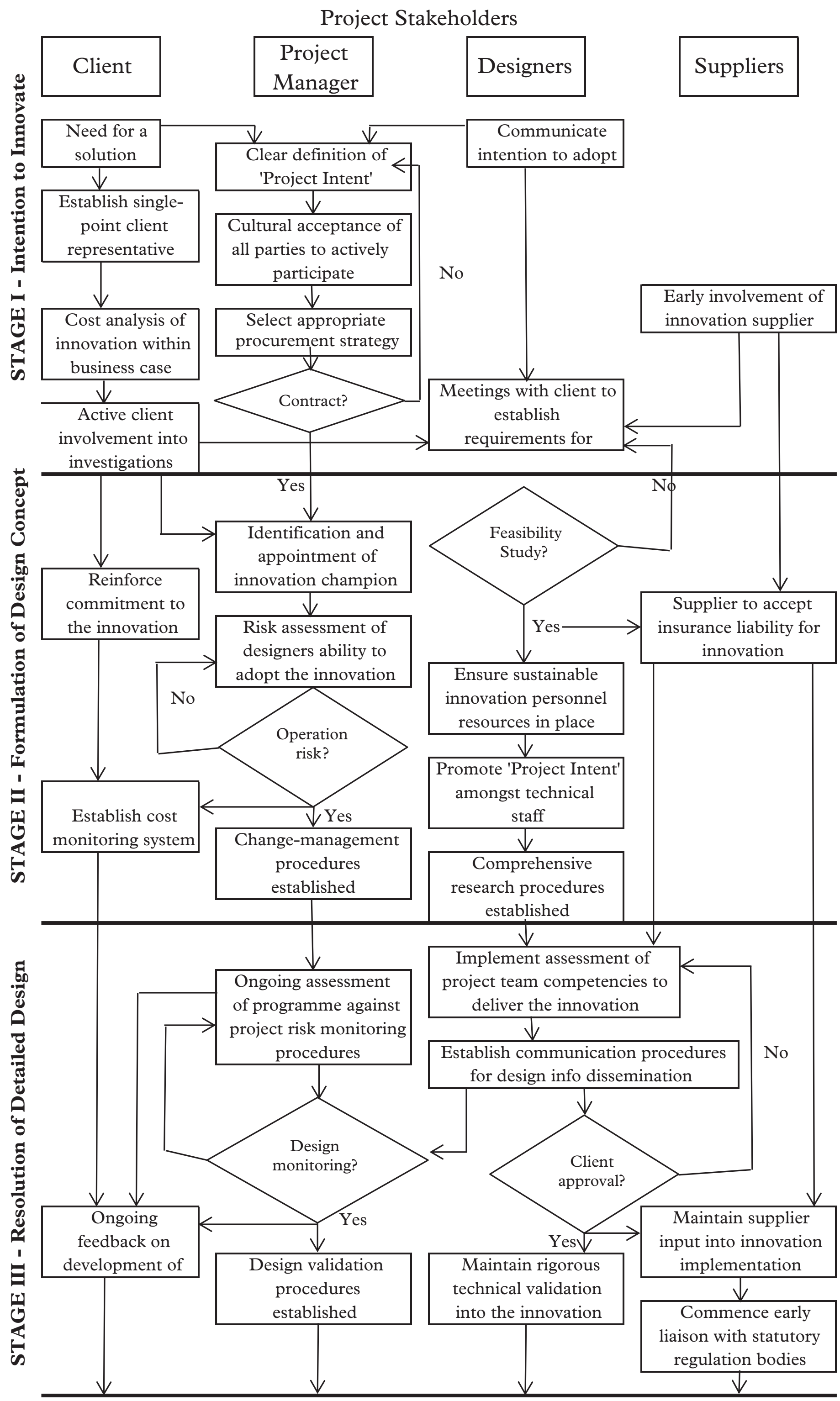

Figure 4a Test model (part A)

their contribution towards a successful innovation, using a Likert scale format. In Round 2 respondents were provided with their previous response as well as mean group score from Round 1, and invited to reconsider their responses. In the third round of the survey the consensus results over the previous two rounds

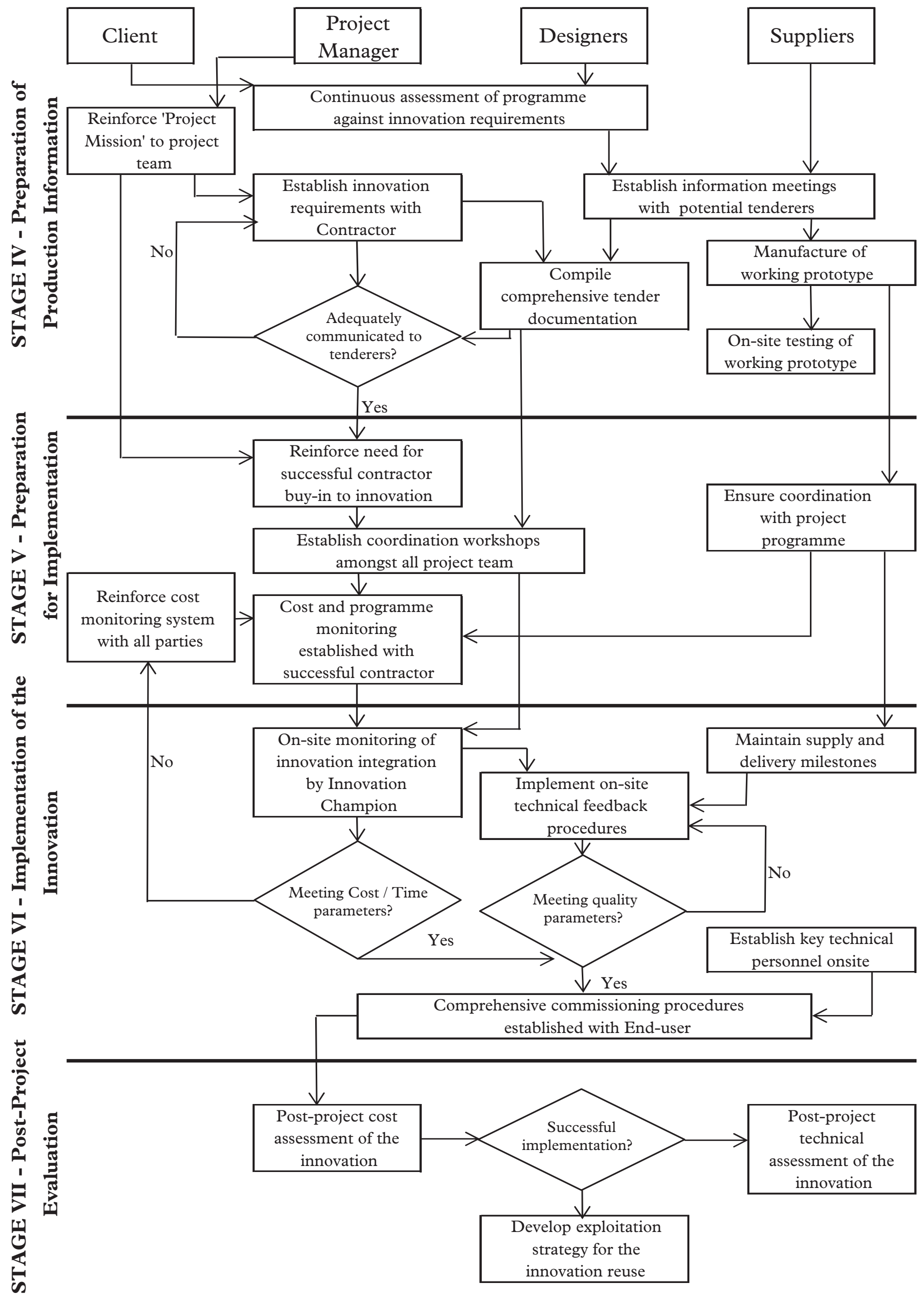

Figure 4b Test model (part B)

were issued for final consideration. A concordance analysis was used to measure the consistency of the experts' responses over successive rounds of the Delphi exercise. Typically, Delphi results have been measured by calculating the inter-quartile range and median of derived data (Shields *et al.*, 1987).

Selection of experts

A contentious aspect of the Delphi method is that of the individual expertise of the panel members (Dalkey *et al.*, 1970). The success of the Delphi method depends principally on the careful selection of the panel of experts (Chan *et al.*, 2001; Yeung *et al.*, 2007). An 'expert' by definition is someone having comprehensive or authoritative knowledge or skill sets in a specific area; however, it was healthcare researchers that identified the lack of literature available to debate the practicalities of defining 'experts' for use within Delphi panel research (Baker *et al.*, 2006). Delbecq *et al.* (1975) provided guidelines on how to solicit qualified participants for a group technique study. The work was further developed by Okoli and Pawlowski (2004) into a multiple-step iterative approach called the knowledge resource nomination worksheet (KRNW). The purpose of the KRNW is to enable categorization of the experts before identifying them. The approach contends that one specific participant panel could not exhibit all the necessary expertise required to do the survey. Therefore it was critical to develop a number of skills groups which would ensure that all potential areas of expertise were covered in the main survey. This ensures that no specific competence or skills group is overlooked (Okoli and Pawlowski, 2004).

For this study three skills groups of participants were used: (1) practitioners; (2) academics; (3) policy-makers. Even within these homogeneous groups it was identified that there were subsets which have diverse competencies. It was therefore required to identify these subsets and include a further range of sub-criteria within each panel group such as professional accreditation and peer-reviewed publications.

Three primary criteria were devised in order to identify eligible participants for this study, namely:

Criterion 1: Having extensive working experience in the implementation of new technology to generate product innovation.
Criterion 2: Having current/recent and direct involvement in the implementation of new technology to generate product innovation.
Criterion 3: Having a sound knowledge and understanding of innovation concepts and their application within construction projects.

In order to obtain the most valuable opinions, only practitioners/academics who met all the selection criteria were considered. A total of 18 experts were identified and invited to participate in the study. The panel represented a wide distribution of professional and academic participants: 10 were industry practitioners; eight were academics of which four were recognized leading experts in the field of innovation management. The names of all selected participants were listed and tabulated with the individual's relevant discipline, skills, qualifications and affiliated company or institution. A list of the panel members and their positions in the corresponding companies and organizations is given in Table 3 although the names of participants and their organizations are abbreviated to respect their anonymity.

Self-rating index

In selection of the panel participants it was recognized that the degree of expertise of the participants could affect the reliability of the results. A means to address the impact of variations in expert opinion was through the use of a self-rating mechanism (Dalkey *et al.*, 1970). The self-rating mechanism is a means of inviting the participants to rate their own expertise, or competence, in the area under discussion. Self-rating usually takes the form of a Likert-style index where expertise is scaled from 1 to 5 indicating scope of expertise as determined by core criteria from the literature (Dalkey *et al.*, 1970). The use of the five-point Likert scale for self-rating is consistent with work by Shields *et al.* (1987). It was considered important that the self-rating score was made *after* the respondent's response to the question to ensure focus on the questions rather than the respondent's competency. Additionally a pilot survey was carried out with an independent panel of three experts (one academic and two practitioners) to secure their feedback to the protocol being employed. On the basis of the pilot survey outcomes a number of refinements were made to the procedures to inform the ongoing research, namely that the assessment of risk be more pointedly addressed in the questions of the follow-up Delphi rounds and the requirement for evidence of the expertise of participants from the self-rating questions to be evaluated against core literature-based criteria.

Delphi Round 1

Round 1 survey questions related to the activities established in the TM. Respondents were asked to evaluate the importance of the TM activities in terms of achieving successful implementation of an innovation. Respondents were asked to indicate a choice based on a five-point Likert scale from 1 to 5 (1 = not important, 5 = extremely important). The questions were listed to reflect their sequence in the TM, i.e. (1) procurement stage at which the activity should occur; (2) stakeholder implicit in the activity; (3) the description of the activity (see Figure 5).

In Round 1, 18 experts were targeted of which 16 responded. The results were analysed by applying the mean as the consensus method. Research has identified that an inter-quartile range of one unit on a five-point scale is representative of a suitable level of consensus. In analysing the 16 validated responses it was necessary to evaluate both the answer to the question as well as the self-rating value. The question response value was multiplied with the self-rating value. This constituted 'weighted' data as opposed to 'unweighted data' which in the question response value was used. In the light of the debate on the significance of self-rating tools, it was decided to calculate the mean values of weighted as against unweighted data. It could then be critically assessed whether there was any statistical significance between the two sets of data and the impact the two

Table 3 List of the panel of experts for the Delphi method

No.	Key groups	Name	Position	Member of a professional body/institute	An academic authority; reviewer in the topic area	Recognized position in the construction industry
1	Industry practitioners with experience in managing innovation	Ms C	Principal	X	–	–
2		Mr N	Principal Partner	X	–	–
3		Mr S1	Principal Partner	X	–	X
4		Mr S2	Director	X	–	
5		Mr T	Chairman	X	–	X
6		Mr McC	Principal Partner	X	–	–
7		Mr M1	Director	X	–	–
8		Mr M2	Partner	X	–	X
9		Mr L	Director	X	–	–
10	Academics with expertise in project management	Dr G	Senior Lecturer	X	X	–
11		Mr J	Director of Education	X		X
12		Dr O	Lecturer	X	X	–
13	Recognized experts in innovation and innovation management	Dr H	Associate Professor	X	X	–
14		Dr M	Project Manager	X	X	–
15		Mr R	Managing Director	X	–	X
16		Dr F	Managing Director	X	–	X

PROJECT STAGE I – Intention to innovate

1. In evaluating the role of the **Client at STAGE I,** how do you rate the following activities, in terms of ensuring a successful innovation:

	Not important	Quite important	Important	Very important	Extremely important
(a) Establishment of a single-point Client representative *(CL/1-In)*	1	2	3	4	5
(b) Early cost analysis of innovation within Client's business strategy *(CL/1-Ct)*	1	2	3	4	5
(c) Active Client/End User involvement into early investigations of the innovation *(CL/1-Cl)*	1	2	3	4	5

Self-rating Index: 1 2 3 4 5
(Please circle as appropriate)

Figure 5 Extract from Delphi questionnaire (Round 1)

mean sets have on the TM data. The unweighted value was the respondent's score to each question whilst the weighted value was the multiplied value of the question score by the self-rating index (SRI). Hence: *Question score SRI = weighted value (1–25)*. A scale was established for both weighted and unweighted data (see Table 4).

Analysis of the weighted and unweighted results in Round 1 suggested that the inclusion of the SRI values (weighted results) produced a moderating effect on the respondent's scores. A *t*-test was carried out on the means of the weighted and unweighted data. The results showed that the two sets of data were extremely statistically significant which confirmed that the SRI was not effectively skewing the results. The impact of the SRI confirmed much of the current debated on effectiveness of self-rating tools. It indicated that if a comprehensive and rigorous protocol is followed unweighted scores should be sufficient to ensure accurate results of the survey.

Using the unweighted data results Table 5 shows the comparison of total frequencies of risk categories between the TM and Round 1 results. It evidenced that 'high' risk categories increased by 14 whilst 'severe' risk categories increased by 6. 'Medium' and 'low' risk categories both decreased by 10 from the TM results.

Table 4 Weighted and unweighted scales correlated to risk categories

Unweighted survey scale			TM risk categories	Weighted survey scale		
0	to	1.25	Low risk	0	to	6.25
1.25	to	2.5	Medium risk	6.25	to	12.5
2.5	to	3.75	High risk	12.5	to	18.75
3.75	to	5	Severe risk	18.75	to	25

There were no 'low' risk frequencies evidenced in the Round 1 results (see Table 5).

Table 5 also showed the comparison of stakeholder competency rankings between the TM and Round 1. Round 1 analysis evidenced a change in the third highest ranking stakeholder competency from the TM thus the critical three stakeholder competencies after Round 1 were (1) technical knowledge; (2) information and communication; (3) organizational culture. Organizational culture had displaced cost management as the more critical competency to manage an innovation.

Delphi Round 2

In Round 2 respondents were asked to evaluate the importance of the TM activities in terms of risk to successful implementation of an innovation: (1) low risk; (2) medium risk; (3) high risk; (4) severe risk. Respondents were provided with their previous score from Round 1 as well as the mean group score and invited to reconsider their previous score, or otherwise, in the light of this information.

Round 2 evidenced a significant shift towards the lower quartile scores compared to Round 1, with the majority of results centred on the 'medium' risk to 'high' risk categories. Total frequency of 'high' risk, 'medium' risk and 'low' risk categories increased by 3, 8 and 3 respectively, whereas there were no 'severe' risk scores evidenced. It could be construed that the participants were reverting to a 'pack' mentality and readjusting their responses to the middle ground (Linstone and Turoff, 1975).

Significantly Round 2 analysis evidenced another change in the third highest ranked stakeholder competency to programme management. Therefore the critical three stakeholder competencies after Round 2 were (1) technical knowledge; (2) information and communication; (3) programme management. Programme management had displaced organizational culture as the more critical competency. It was clear that by the end of Round 2 the two most critical stakeholder competencies were still technical knowledge and information and communication.

Delphi Round 3

In Round 3 respondents were provided with the consolidated results from Round 2 and again invited to reconsider their previous scores. The results of Round 3 evidenced a conclusive swing back to the broad range of results which had been evidenced in Round 1 (see Table 6). There was an even distribution of risk rankings across all the risk categories as opposed to the convergence at 'high' risk for over 54% of the activities in Round 2. Also the critical five stakeholder competencies were identical in Round 3 to Round 2, i.e. (1) technical knowledge; (2) information and communication; (3) programme management; (4) organizational culture; and (5) cost management.

Delphi results

Recent literature has advanced the approach that innovation should be delivered through a process-based stakeholder competency approach rather than traditional project management approaches (Edum-Fotwe and McCaffer, 2000; Lampel, 2001; Dainty *et al.*, 2005; Murphy *et al.*, 2013). The Delphi survey established the critical stakeholder competencies required for successful delivery of a product innovation are: (1) technical knowledge; (2) information and communication; (3) programme management. Technical knowledge is concerned with the level of understanding of the new technology and the competency to apply that understanding within a management context. Historically technical complexities and limitations in technology adoption have focused on investigations of collaborative working (Kiviniemi *et al.*, 2008) and failed to maintain insights into *technical knowledge* competence. However there is strong evidence of recent studies addressing *technical knowledge* competence to implement new technologies (Lee *et al.*, 2006; Steel *et al.*, 2012; Ibrahim and Moselhi, 2013; Migilinskas *et al.*, 2013). Programme management is concerned with the integration of the implementation process with the project management process. Much of the recent research into *programme management* competence has focused on documenting the impact of new technologies using benchmarking tools such as key performance indicators to assess the impact on site-based technology implementation such as building information modelling (BIM) (Azhar *et al.*, 2008; El Asmar and Francom, 2013). This study suggests that the early appointment of an innovation champion (Stage I) is critical for documenting and monitoring the implementation of a new technology. However it was found that this is only effective where there is a competent project manager in place and would suggest that strong project management skills are required to support the

Table 5 Comparison of risk rankings across Delphi rounds

Risk ranking categories	Test model Total frequency	Test model Percentage (%)	Round 1 Total frequency	Round 1 Percentage (%)	Round 1 Change + –	Round 2 Total frequency	Round 2 Percentage (%)	Round 2 Change + –	Round 3 Total frequency	Round 3 Percentage (%)	Round 3 Change + –
Severe	8	17	14	29	6 +	0	0	14 –	21	44	21 +
High	12	25	26	56	14 +	30	63	3 +	15	31	15 –
Medium	18	37	8	15	10 –	15	31	8 +	11	23	4 –
Low	10	21	0	0	10 –	3	6	3 +	1	2	2 –

Table 6 Comparison of stakeholder competency rankings across Delphi rounds

Test model analysis Stakeholder competency	Total frequency	Risk ranking Severe	High	Medium	Low	Ranking	Delphi Round 1 analysis (unweighted) Stakeholder competency	Total frequency	Risk ranking Severe	High	Medium	Low	Ranking	Delphi Round 2 analysis Stakeholder competency	Total frequency	Risk ranking Severe	High	Medium	Low	Ranking	Delphi Round 3 analysis Stakeholder competency	Total frequency	Risk ranking Severe	High	Medium	Low	Overall ranking
Technical knowledge	13	4	4	1	4	1st	Technical knowledge	13	3	7	3		1st	Technical knowledge	13		9	2	2	1st	Technical knowledge	13	4	5	4		1st
Information and							communication	10	1	1	5	3	2nd	Information and communication	10	3	6	1		2nd	Information and communication	10		6	4		2nd
Information and communication	10	5	1	4		2nd																					
Cost management	5	1		4		3rd	Organizational culture	4	3	1			3rd	Programme management	8		5	3		3rd	Programme management	8	4	3	1		3rd
Organizational culture	4	1	1		2	4th	Programme management	8	2	6			4th	Organizational culture	4		4			4th	Organizational culture	4	3	1			4th
Personnel management	2	1		1		5th	Cost management	5	1	2	2		5th	Cost management	5		2	3		5th	Cost management	5	2	1	2		5th
Programme management	8		1	6	1	6th	Planning and administration	3	1	1	1		6th	Planning and administration	3		2		1	6th	Personnel management	2	2				6th
Organizational strategy	3		3			7th	Personnel management	2	1	1			7th	Organizational strategy	3		1	2		7th	Planning and administration	3	1	1		1	7th
Planning and							administration	3		2	1		8th	Organizational strategy	3		2	1		8th	Personnel management	2		1	1		8th
Organizational strategy	3		3			8th																					
Totals	48	8	12	18	10		Totals	48	14	26	8			Totals	48		30	15	3		Totals	48	21	15	11	1	

work of an innovation champion. Information and communication relates to the level of interaction evidenced amongst project stakeholders during the adoption and implementation stage. It is well documented that issues of stakeholder collaboration and integration are crucial to the long-term success of new technology (Kiviniemi *et al.*, 2008; Zuppa *et al.*, 2009; Sacks *et al.*, 2010; Dossick and Neff, 2011; Ho and Feng, 2013). The Delphi findings in this study also suggest that inconsistent communication transfer, particularly at the early development stages (Stage III), is a key factor in technology failure. Effective information control and communication transfer exhibited by stakeholders early in the process drove successful implementation of the technology in the latter stages of the project (Stage VI).

Conclusions

Product innovation in the construction industry brings considerable benefits to all construction stakeholders. However unlike other sectors construction has historically failed to generate and sustain innovation to harness these benefits. There are well-established reasons for this not least the historic separation of the design and construction stages of the development process. Consequently new technology adopted during the design stages struggles to survive through the construction stage to fulfil implementation. It requires effectively managing the project process to mitigate this potential for failure. However, innovation, by virtue of its definition, is an iterative process which cannot be confined within the rigid constraints of a sequential project management process. Recent studies have argued that innovation requires a great deal of flexibility within projects and that the effective management of such flexibility depends on the acquisition and development of competency in the stakeholders (Dulaimi and Kumaraswamy, 2000; Edum-Fotwe and McCaffer, 2000; Lampel, 2001; Keegan and Turner, 2002; Cooper *et al.*, 2005; Dainty *et al.*, 2005; Murphy *et al.*, 2011; Perera *et al.*, 2013). Therefore a process management approach, delivered in conjunction with the project management process, was proposed as the means through which to deliver innovation. Whilst there have been influential studies to develop the research around innovation management the outputs have been largely theoretical and there is a gap in the development of a practical tool for facilitating successful implementation of innovation into construction projects.

This study is a development on previous work which produced two theoretical constructs for the successful implementation of a new technology into a building: the innovation management flowchart (IMF) and the constraint classification matrix (CCM). Whilst both constructs held important information required to sustain innovation their value for practical application into the industry was limited. Therefore it was proposed to determine whether the two constructs (IMF and CCM) could be integrated into a practical tool for generating innovation in an industrial context. A method using process modelling and statistical analysis was established to integrate the constructs. The approach comprised extraction of the data from each construct using statistical analysis and failure model and effect analysis (FMEA). A process template was developed which established a framework into which the extracted data from the two constructs was populated. The output of the alignment process was a test model. The test model was subject to three rounds of Delphi using 18 experts to gain a consensus on the test model outputs. The result of the Delphi process was an innovation management model (IMM).

The primary outcome of this study is the development, testing and validation of a model to mitigate the risk of abandonment of new technology implementation due to the operation of uncontrolled constraints. The IMM establishes a systematic sequence of prioritized activities required to manage the effective implementation of a new technology into a construction project, using core stakeholder competencies, to generate product innovation. The IMM, as a process model, can be used repeatedly across numerous construction projects to implement a new technology.

Previous studies have shown that process models provide potentially valuable tools for industrial use by developing effective, easy-to-use collaborative working methods which can be adopted by project stakeholders (Wix and Katranuschkov, 2002). The IMM is a simple, flowchart format which reflects the requirement of an industry that has historically resisted overcomplicated modelling arrangements to convey simple, effective precepts. Practically, the activities from the IMM can be extracted to facilitate the development of programming software to integrate the activity requirements of the innovation with the project programme. The programme can then be used as part of risk management workshops to inform the ongoing management of the project.

The IMM has implications for the selection of procurement methods. The key sources of innovation in the construction industry have commonly been identified as contractors, suppliers and manufacturers (Von Hippel, 1988; Slaughter, 1998). The IMM used in conjunction with integrated procurement methods can increase control of the implementation process thus reducing the inherent risk of premature failure of the innovation. It allows the main contractor or the project manager to implement the IMM tool to manage risks related to the implementation of the technology. Furthermore it will encourage increased levels of product development from within the industry thus reducing the high levels of technology transfer from other sectors.

The IMM will instil confidence in clients and designers in sourcing and adopting new, untested technologies in the knowledge that a new product can be successfully implemented into a building and its benefits realized. The IMM tool provides a stakeholder specific view to the process of managing innovation within the design and construction stages of a project. Each stakeholder can use the tool to guide their input towards sustaining the innovation. This has implications for competency mapping of personnel within projects as well as participating firms. It will inform targeted skills training and continuing professional development (CPD) of key stakeholders to develop and advance their competencies to manage new technology implementation. This, in turn, has the potential to reverse the tide of poor innovation rates in the construction industry and thus improve economic growth. Since the construction industry currently lacks the mechanisms to effectively adopt and implement innovation the IMM provides insights as to how a competency-based approach may address this knowledge gap and provide a practical tool for increasing the rate of successful innovation uptake in the construction industry.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix 1

Schedule of construct data (SoCD)

Test Model															
	Constraint Classification Matrix									Innovation Management Flowchart		Delphi Rounds			
STAGE I - Intention to Innovate															
Activity code	Innovation constraint	Implicit stakeholder	Competency failure	Process Stage		O	S	D	RPN	Management response activity	**Activity risk ranking**	Round 1 Unweighted	Round 1 Weighted	Round 2	Round 3 (IMM)
				Cause	Effect										
A1	Lack of clarity in Client requirements	Client	Information and Communication	I	I	6	8	6	288	Establish single-point client representative	Medium	High	Medium	High	Medium
A2	Non-alignment of business needs with innovation	Client	Cost Management	II	II	6	4	3	72	Early cost analysis aligned with business strategy	Medium	High	Medium	Medium	Medium
A3	Failure to involve client in Supplier investigations	Client	Culture and Values	I	I	7	8	3	166	Active user involvement in product development	Low	Severe	High	High	Severe
A4	Conflict amongst groupings of the project team	Project Manager	Information and Communication	II	II	6	8	3	144	Establish clear definition of 'Project Intent'	Low	Severe	High	High	Severe
A5	Failure to align stakeholder expectations	Project Manager	Strategy and Policy	V	IV	7	8	6	336	Cultural acceptance by all parties to participate	High	High	Medium	Medium	High
A6	Contract clause inadequate to facilitate innovation	Project Manager	Planning and Administration	I	I	6	7	7	294	Selection of appropriate procurement strategy	High	High	Medium	High	High
A7	Lack of clarity in business benefits and incentives	Designer	Information and Communication	V	V	5	4	5	100	Communicate intention to adopt innovation	Medium	High	High	High	Medium
A8	Client reticence to proceed due to poor team buy-in	Designer	Culture and Values	I	I	7	6	4	168	Establish client meetings to establish requirement	Low	Severe	High	High	Severe
A9	Lack of early supplier involvement with the design	Supplier	Technical	II	II	6	8	3	144	Supplier involvement in design development	Low	Severe	Medium	High	High

Test Model															
	Constraint Classification Matrix									Innovation Management Flowchart		Delphi Rounds			
STAGE II - Formulation of Design Concept															
Activity code	Innovation constraint	Stakeholder	Competency	Process Stage		OSD			RPN	Management activity	**Activity risk ranking**	Round 1 Unweighted	Round 1 Weighted	Round 2	Round 3 (IMM)
				Cause	Effect										
A10	Client uncertainity about return on investment	Client	Information and Communication	II	II	6	4	3	72	Establish early client commitment to innovation	Medium	High	Medium	Medium	Medium
A11	Lack of independent financial advice to the Client	Client	Cost Management	VI	IV	8	7	6	360	Rigorous early cost analysis of adoption costs	Severe	Medium	Medium	Medium	Severe
A12	No identifiable Innovation Champion	Project Manager	Strategy and Policy	I	I	6	7	4	168	Identify and appoint Innovation Champion	High	High	Medium	High	High
A13	Poor technical knowledge of innovation by design staff	Project Manager	Information and Communication	II	I	7	8	6	336	Risk assessment of designers competency	Medium	Medium	Medium	Medium	Medium
A14	No formal change-management system	Project Manager	Programme Management	IV	IV	7	7	7	343	Establish change-management protocol	Medium	High	Medium	Medium	Severe
A15	Failure to provide adequate resources for staff	Designer	Human Resources	II	II	7	6	5	210	Ensure sustainable personnel (HR) in place	Severe	Severe	High	High	Severe
A16	Non-proactive information transfer by Designer staff	Designer	Culture and Values	II	I	6	8	6	288	Promote 'Project Intent' amongst technical staff	Severe	High	Medium	High	Severe
A17	Cursory research into design problem	Designer	Technical	II	II	7	7	5	245	Establish R&D procedures/monitoring	Severe	Medium	Medium	Medium	Medium
A18	Failure of supplier to obtain the necessary insurances	Supplier	Planning and Administration	II	II	5	5	4	100	Agree insurance liabilities with supplier	Medium	Medium	Low	Low	Low

Test Model															
	Constraint Classification Matrix									Innovation Management Flowchart		Delphi Rounds			
STAGE III - Resolution of the Detailed Design															
Activity code	Innovation constraint	Stakeholder	Competency	Process Stage		O	S	D	RPN	Management response activity	**Activity risk ranking**	Round 1 Unweighted	Round 1 Weighted	Round 2	Round 3 (IMM)
				Cause	Effect										
A19	Concerns at End-user non-participation in discussions	Client	Technical	I	I	7	6	4	168	Establish client feedback control mechanisms	Low	High	Medium	Medium	Medium
A20	Late submission of risk register by key stakeholders	Project Manager	Programme Management	V	IV	6	6	5	180	Assess programme with risk control measures	Medium	High	Medium	Medium	Severe
A21	Inaccuracies of structural information for fabrication	Project Manager	Information and Communication	V	IV	8	5	7	280	Establish design validation controls	Medium	High	Medium	Medium	Severe
A22	Lack of client confidence in coordination of team info.	Designer	Technical	I	I	8	7	3	168	Strategic assessment of innovation with Client	High	High	Medium	High	High
A23	Inconsistencies between information across team	Designer	Information and Communication	III	II	8	8	5	320	Establish procedures for design communication	High	Severe	High	High	High
A24	Probematic integration with associated systems	Designer	Technical	II	II	7	7	5	245	Technical analysis of innovation amongst team	High	Severe	High	High	High
A25	Lack of early integration of Supplier into team meetings	Supplier	Information and Communication	V	VI	8	7	7	392	Establish regular Supplier input to project	Low	High	Medium	Medium	Severe
A26	Failure of 'innovation intent' to meet Building Regulations	Supplier	Technical	III	II	7	8	6	336	Early liaison with statutory agencies / bodies	Low	High	Medium	Medium	Severe

Test Model												Delphi Rounds			
	Constraint Classification Matrix									Innovation Management Flowchart					
STAGE IV - Preparation of Production Information															
Activity code	Innovation constraint	Stakeholder	Competency	Process Stage Cause	Process Stage Effect	O	S	D	RPN	Management response activity	**Activity risk ranking**	Round 1 Unweighted	Round 1 Weighted	Round 2	Round 3 (IMM)
A27	Omission of key associated work packages	Project Manager	Technical	IV	IV	7	7	6	294	Review programme against innovation requirements	Medium	High	Medium	High	High
A28	Lack of management support for innovation adoption	Project Manager	Human Resources	V	VI	6	9	3	162	Reinforce 'Project Intent' to project team	High	High	Medium	Medium	High
A29	Insufficient allowance for innovation in tendering period	Project Manager	Planning and Administration	IV	II	7	9	6	378	Establish innovation-focused tendering process	High	Severe	Medium	High	Severe
A30	Lack of information in tender documents	Designer	Information and Communication	V	IV	8	5	7	280	Innovation briefing meetings with potential tenderers	Low	High	High	High	Severe
A31	Failure of supplier to meet tender programme	Designer	Technical	IV	II	5	7	6	210	Preparation of innovation tender documentation	High	High	High	High	High
A32	Lack of independent anlaysis on design models	Supplier	Technical	III	II	7	10	7	490	Manufacture of innovation prototype	Severe	Medium	Medium	Low	Severe
A33	Failure of concrete castings at installation stage	Supplier	Programme Management	IV	II	7	9	7	441	Early testing of working innovation prototype	Low	High	Medium	Medium	Severe

Test Model												Delphi Rounds			
	Constraint Classification Matrix									Innovation Management Flowchart					
STAGE V - Preparation for Implementation															
Activity code	Innovation constraint	Stakeholder	Competency	Process Stage Cause	Process Stage Effect	O	S	D	RPN	Management activity	**Activity risk ranking**	Round 1 Unweighted	Round 1 Weighted	Round 2	Round 3 (IMM)
A34	Cost of optic fibres exceeded project budget	Client	Cost Management	III	II	8	8	5	320	Establish innovation cost monitoring mechanism	Medium	Severe	Medium	High	Severe
A35	Lack of motivation by team members	Project Manager	Culture and Values	V	IV	6	6	4	114	Ensure tenderer 'buy-in' to the innovation	High	Severe	High	High	High
A36	Incorrect costing of innovation by tenderers	Project Manager	Information and Communication	IV	IV	6	7	5	210	Establish innovation workshops amongst team	Severe	High	Medium	Medium	Severe
A37	Lack of coordination of building trades on site	Project Manager	Programme Management	VI	IV	8	6	5	240	Establish project controls with construction team	High	Severe	High	High	High
A38	Inadequate allowances for sourcing and delivery	Supplier	Programme Management	IV	III	6	6	7	252	Ensure coordination with project programme	Medium	Severe	Medium	High	High

Test Model												Delphi Rounds			
	Constraint Classification Matrix									Innovation Management Flowchart					
STAGE VI - Implementation of the innovation															
Activity code	Innovation constraint	Stakeholder	Competency	Process Stage Cause	Process Stage Effect	O	S	D	RPN	Management response activity	**Activity risk ranking**	Round 1 Unweighted	Round 1 Weighted	Round 2	Round 3 (IMM)
A39	Failure to meet cost estimates	Project Manager	Cost Management	VI	III	5	7	5	175	Ensure on-going cost milestones are met	Medium	High	Medium	High	High
A40	Inadequate, inexperienced site supervision	Project Manager	Programme Management	III	II	7	8	7	392	Ensure programme milestones are met	Medium	High	Medium	High	Severe
A41	Concerns at adequacy of the commissioning process	Project Manager	Technical	VI	IV	7	8	6	336	Establish agreed commissioning procedures	High	High	Medium	High	Severe
A42	Acceptance of unsatisfactory work practices	Designer	Technical	VI	III	7	8	6	336	On-site monitoring of innovation integration	Severe	High	High	High	Severe
A43	Late integration of specialist sub-contractor requirements	Supplier	Programme Management	V	VI	5	8	5	200	Supplier to maintain service milestones	Medium	High	High	High	Medium
A44	Delays due to non-diligent site inspection	Supplier	Technical	VI	V	7	6	6	252	Establish on-site technical feedback procedures	Severe	High	High	High	Severe
A45	Delays to installation due to non-availability of Supplier	Supplier	Information and Communication	VI	VI	3	8	5	120	Post permanent Supplier personnel on site	Medium	Severe	High	High	Severe

Test Model												Delphi Rounds			
	Constraint Classification Matrix									Innovation Management Flowchart					
STAGE VII - Handover															
Activity code	Innovation constraint	Stakeholder	Competency	Process Stage Cause	Process Stage Effect	O	S	D	RPN	Management activity	**Activity risk ranking**	Round 1 Unweighted	Round 1 Weighted	Round 2	Round 3 (IMM)
A46	Failure to maintain bespoke records of the innovation	Project Manager	Cost/Time Management	V	IV	6	6	4	114	Cost/Programme analysis of implementation	Medium	Medium	Medium	Medium	Medium
A47	Disbandment of key project personnel post-handover	Designer	Technical	II	II	3	2	2	12	Focused exploitation strategy for re-use	Low	High	Medium	High	High
A48	Poor stakeholder evaluation of innovation post-handover	Supplier	Technical	V	IV	4	6	5	120	Technical review of implementation	Medium	High	Medium	High	Medium