The adoption of 4D BIM in the UK construction industry: An Innovation Diffusion approach

Purpose - More than half of UK construction projects exceed their planned time schedules. This is a trend that has been recorded over a number of years using standard industry KPI data. Despite these failings, UK Government introduced a strategic target of delivering future projects 50% faster than the project durations achieved in 2013. To realise this strategy requires, amongst other things, more rapid project delivery processes, and consistent improvements to the time predictability aspects of on-site construction delivery periods. There is an expectation, supported by some evidence, that the adoption of 4D BIM by UK project planners will contribute to this. The aim of the present research was to investigate how this adoption has taken place, using Rogers' Innovation Diffusion theory as a basis.

Design/methodology/approach – A survey of 97 construction planning practitioners was conducted to measure 4D BIM innovation take-up over time. Classic innovation diffusion research methods were adopted.

Findings – Analysis of the data addresses how the benefits of 4D BIM are being realised and explore reasons for adoption or rejection decisions of this innovation. Results indicated an increasing rate of 4D BIM adoption and reveal a time lag between awareness and first use that is characteristic of this type of innovation.

Research limitations/implications – Use of a non-probability sampling strategy prevents the results being generalisable to the wider construction population. Several

possible future research directions and methods are advised. These include

qualitative investigations into the decision making process around 4D BIM, and case

study exploration of the consequences of 4D BIM innovation adoption.

Practical implications – Recommendations of how to facilitate the adoption of 4D

BIM innovation are proposed, which identify the critical aspects of system

compatibility and safe trialling of the innovation.

Originality / Value - This paper reinforces 4D BIM as an innovation and records its

actual UK industry adoption rate using an accepted diffusion research method. By

focusing on UK industry-wide diffusion the work also stands apart from more

typical research efforts that limit innovation diffusion exploration to individual

organisations.

Paper Type – Research paper

Keywords - 4D planning, Building Information Modelling (BIM), Construction

planning, Innovation, Diffusion.

Introduction

Emphasis on the time performance of UK construction industry was documented in a

recent governmental strategy report (HM Government, 2013) where a 'Vision for

2025' presented requirements for 50% faster UK project delivery benchmarked

against 2013 industry performance. Data has revealed a downward trend in UK

construction project time predictability. 2012 KPI's reported the lowest figures over

a 12 year period, when no more than 34% of UK construction projects were delivered on or before their original planned project end date, and only 42% of construction phases delivered on or before their original planned completion date (Gledson, 2015; Gledson and Greenwood, 2014). Table 1 and Figure 1 show the KPI data reported for measures of construction time predictability in years 2007 to 2015. Whilst the latest data reveal a small improvement across all three measures of time predictability, it is clear that more than half of UK construction projects continue to exceed their agreed time schedules.

Table 1: Construction time predictability for years 2007 - 2015 - percentage of projects and phases delivered on time or better. Table adapted from Constructing Excellence (2016)

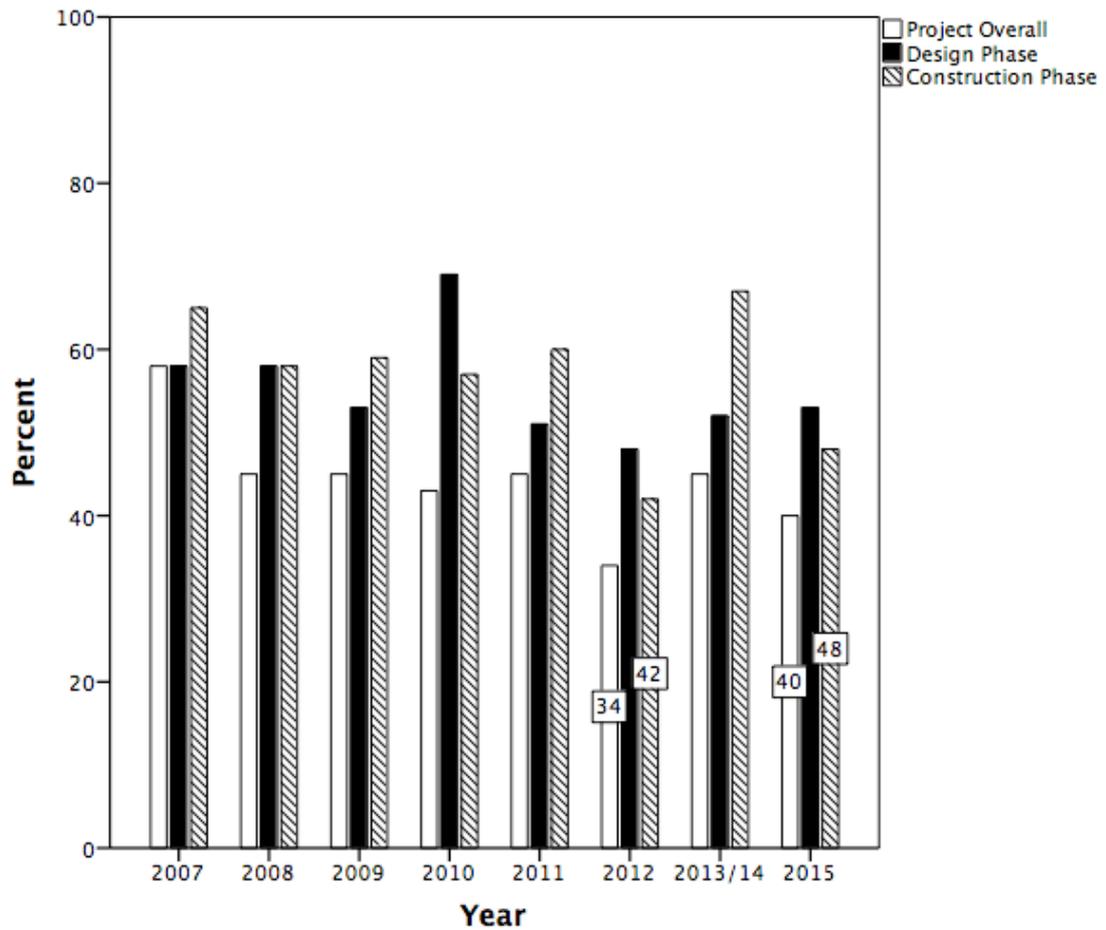| KPI (%). Proportion on time or better.	2007	2008	2009	2010	2011	2012	2013/14	2015
Predictability Time: Project Phase	58	45	45	43	45	34	45	40
Predictability Time: Design Phase	58	58	53	69	51	48	52	53
Predictability Time: Construction Phase	65	58	59	57	60	42	67	48

Figure 1: Construction time predictability for years 2007 - 2015, percentage of projects and phases delivered on time or better. Table adapted from Constructing Excellence KPI's (2016)

Poor construction cost and time predictability can be attributed to a number of causes. These include: the unforeseen impact of delays (González et al., 2013; Larsen et al., 2015); project complexity such as size, construction methods and technology used; and the inefficient organisation of human resource (Love et al., 2013; Olaniran et al., 2015). González et al (2013) identified poor planning, rather than unforeseeable events, as the greatest contributor to poor time performance. Planning quality is determined by the effectiveness of the planning process. Design and production information act as key inputs to the planning process, and the

transformation of these inputs into planning output is further affected by the competencies, judgements and biases of the persons advising about, and undertaking, planning operations. Subsequent plan execution is also subject to similar factors during plan interpretation, as well as issues revolving around resource deployment and management. Crotty (2012) argues that traditional forms of information used to plan and realise construction projects have been of "*devastatingly poor quality*" and also asserts that the use of Building Information Modelling (BIM) offers "*far higher quality design information*". Any improvements in the information quality which is used as inputs for the planning process, should therefore positively affect planning quality, planning output, and possibly improve the predictability of project delivery. Commonly used definitions of BIM revolve around representations of product and process. Turk, (2016) provides a compelling and comprehensive analysis of what BIM is, and makes distinctions between the locations where BIM use and benefits are 'pushed' through research and education, and locations such as the UK where it has effectively been demanded in the Government Construction Strategy (HM Government, 2011) for centrally procured public projects. Such a mandate makes any study of the diffusion of BIM relevant within the UK context. A key benefit of the introduction of BIM is its use in the planning of projects. '4D BIM' is acknowledged as a useful addition to construction planning methods as it produces construction process visualizations (Hartmann and Vossebeld, 2013) which enables better understanding (Heesom and Mahdjoubi, 2004; Wang et al., 2004) and decision making (Hartmann et al., 2008). The aim of the current study is neither to support or challenge these assertions, but rather to examine the process through which the innovation of 4D BIM has been communicated to and adopted by UK construction planners over time. To do this, use is made of Rogers (2003) Innovation Diffusion

Theory (IDT). This satisfies calls by researchers (Kale and Arditi, 2010; Reichstein et al., 2005) who assert that too few surveys of innovation in construction use recognised theoretical models, despite their validity and appeal across broader academic communities.

Conventional construction planning

Construction planning is required to determine the project duration against which performance is measured (Gledson and Greenwood, 2016). Planning is performed in order to decide upon organisational goals and project means and solutions (Winch and Kelsey, 2005). Plans have traditionally been communicated in a variety of formats, most frequently in bar charts mediums using computer aided scheduling software to perform critical path calculations. Construction projects have a need for systematic and rigorous front-end planning, yet managers are encouraged to question prevailing solutions (Greenwood and Gledson, 2012). Construction programmes can also suffer from systems complexity, with the volume of *Tasks Per Programme* (TPP) being one indicator of such complexity. This has been illustrated in previous research efforts where Liston *et al.* (2001) used a typical construction programme that contained 8,000 tasks, and Dawood (2010) used a quantitative technique to demonstrate that 15,631 tasks were identified across two construction projects. In addition to TPP volume, another indicator of programme complexity is the multiplicity of logical dependencies and different dependency types (e.g. Finish to Start; Start to Start; Start to Start with Lag dependencies) that are applied to each individual task, meaning that increases in the number of possible logical iterations also increase the complexity of the programme. Furthermore, Hartmann and

Vossebeld (2013) have outlined the distinct challenges in planning the assembly of site constrained construction products that requires the integration of knowledge across multiple product co-creators and project actors and identify the need for greater clarity in knowledge transfer when facilitating communication about complex construction processes.

Communication and problems of transactional distance

Effective communication is a significant factor in any successful project (Gorse and Emmitt, 2007; 2009). Communication involves iterative processes containing multiple components set against a background of 'noise' (Emmitt, 2010). Components include: the message; any necessary coding of the message; senders; receivers; channels of communication; and some form of feedback to identify communication comprehension. Although senders trust that they have sent clear messages, doubts may remain as to whether these messages have been received and processed as intended. Various communication models have been developed, including early simple linear (Sender-Message-Channel-Receiver) models (Berlo, 1960; Shannon and Weaver, 1949) and later (Encode-Transmit-Receive-Decode) transactional models of communication (Barnlund, 2008) that recognise the importance of coding, communication noise, and feedback to test comprehension. Communication effectiveness relies on the success of closing the transactional distance between parties. 'Transactional distance' theory was developed by Moore (1993) and is defined as being the psychological distance that exists between people when communicating (Barrett, 2002 as cited by Soetanto et al., 2014). All forms of construction production information, such as drawings, specifications and schedules,

are generated by a sender attempting to communicate a message. Often the receiver of production information struggles to understand exactly what has been updated, or what is communicated (Li *et al.*, 2011). One benefit of the use of Building Information Modelling (BIM) is the resultant improvement in the quality of production information (Crotty, 2012) and whilst its use helps close the transactional distance between construction actors, it is believed that through the construction process visualizations, the use of 4D BIM can reduce this gap further.

Closing transaction distance through the diffusion of 4D BIM innovation

Gledson (2016, p230) has described BIM as a "*radical, transformative and disruptive innovation*". As such, BIM conforms to Everett Rogers definition of an innovation - "*an idea, practice or object that is perceived as new by an individual or other unit of adoption*", where diffusion is the "*process through which an innovation is communicated through certain channels and adopted over time among the members of a social system*" (Rogers, 2003). A comprehensive review of innovation diffusion literature undertaken by Hosseini et al (2015) identified the fundamental characteristics of construction innovations as: being new to the employing organisation(s); producing non-trivial change(s); forecasting process linked benefits; generating outcome value; delivering competitive advantages; subject to both risk and uncertainty; and introducing practices unfamiliar to construction. Much of these attributes apply to the use of 4D BIM. Literature considers the use of 4D BIM innovation, where the time dimension is linked to the 3D-model $(x + y + z + t)$ as a useful addition to construction planning (Koo and Fischer, 2000). As noted,

construction planners traditionally use a programme in order to communicate their own message, i.e. the plan. However this medium can impede the intended message (Cullen and Nankervis, 1985). 4D planning involves making use of 4D BIM to improve construction-planning techniques. 4D planning is when a time schedule is linked to a 3D-model to enable visualisation of the time and space relationships of construction activities (Buchmann-Slorup and Andersson, 2010; Liston *et al*., 2001). 4D Planning facilitates greater analyse of the construction schedule to assess its implementation (Koo and Fischer, 2000; Mahalingam et al., 2010; Trebbe et al., 2015), and help reduce scheduling errors through plan interrogation and validation. 4D BIM aims to amplify the understanding of the construction plan through 4D visualisations which are *"simpler representations of the development of the project and can be used by a wider variety of project participants at varying levels of skills and experience"* (Mahalingam et al., 2010). Other planning related benefits of 4D BIM include more effective coordination and review practices (Hartmann and Fischer, 2007; Olde Scholtenhuis et al., 2016), better planning and management of on-site space and resources (Kassem et al., 2015; Wang et al., 2004), and use of automated construction progress tracking capabilities (Kim, Kim, et al., 2013; Kim, Anderson, et al., 2013).

Problems of resistance and diffusion

Several researchers consider there to be an increase in the uptake of construction professionals using 4D BIM innovation (Hartmann et al., 2008; Hartmann and Fischer, 2007; Trebbe et al., 2015). The gap between theoretical benefits, of communication and operational efficiencies espoused within the literature, and actual

use within industry has been noted (Mahalingam et al., 2010) and because of the practical difficulties of implementing 4D BIM there is a need to further explore implementation and perceptions of intended users towards this innovation. Organisational and project related barriers have impeded the widespread diffusion of 4D BIM innovation and despite the apparent advantages afforded by 4D BIM, it should be noted that any misunderstanding by planners and construction practitioners will impede diffusion (Li *et al.*, 2008), equally there is likely to be human resistance to such innovation. A significant frustration for practitioners are the challenges faced when changes to working processes are introduced, particularly having to learn new software, after years of gaining a particular expertise. Industry professionals such as construction planners are likely to strongly identify themselves by the professional and technical expertise skills that they have acquired over a long period, synthesising their experiences over each project. Dodgson and Gann (2010) identify that such disruptive innovations are likely to disturb the balance and implicit social contracts that lie between organisations and employees. Mahalingam *et al.* (2010) identified that organisational and project related barriers have impeded the widespread diffusion of 4D BIM and warned that despite these benefits the innovation *"might not diffuse through the construction industry unless 4D modelling and analysis is integrated into existing project planning approaches"*. There is a need therefore to consider 4D BIM innovation from the perspective of innovation diffusion theory. Previous research (Gledson and Greenwood, 2014; 2016) into the implementation and use of 4D BIM and virtual construction (VC) found high levels of BIM awareness with some experience of use of VC, primarily for work winning, methods planning, and the visualisation and validation of construction processes. These researchers identified an opportunity for further research: the need to see if the

potential benefits of 4D planning are being actualised to provide greater efficiency

and effectiveness over traditional methods of planning construction projects. An aim

of this study is to address this opportunity.

Research Method

The target population of the study was all construction disciplines working for or

with contracting organisations delivering construction projects across any tier of the

UK construction industry. An online web hosted questionnaire survey was

considered an appropriate means of data collection and purposive sampling was

employed. Analysis of the available data suggest that 1,650,000 workers fit this

profile at any one time (Myers, 2013) which was the assumed population size for this

study. A questionnaire survey can be considered to be an appropriate means of data

collection for this study (Easterby-Smith *et al*., 2008; Fellows and Liu, 2008). The

survey was undertaken in 2015 and collected 97 full responses. An additional 54

partial responses were received although these were excluded from analysis due to

their incompleteness. In order to determine the rate of adoption of 4D BIM

innovation, the research design was approached from the perspective of classic

innovation diffusion theory, represented by the work of Rogers (2003) A 5-part

questionnaire containing 49 questions was formulated using several of Rogers' key

variables which were adapted to measure the rate of 4D BIM adoption (See Figure

2). These variables included the perceived attributes of the innovation, namely: the

relative advantages of 4D BIM innovation against functions of construction

planning; the relative advantages of 4D BIM innovation against stages of the

construction planning process; issues of compatibility, complexity, trialability and

observability. Other independent diffusion research variables that were measured included information regarding communication channels, and the types of innovation decisions made.
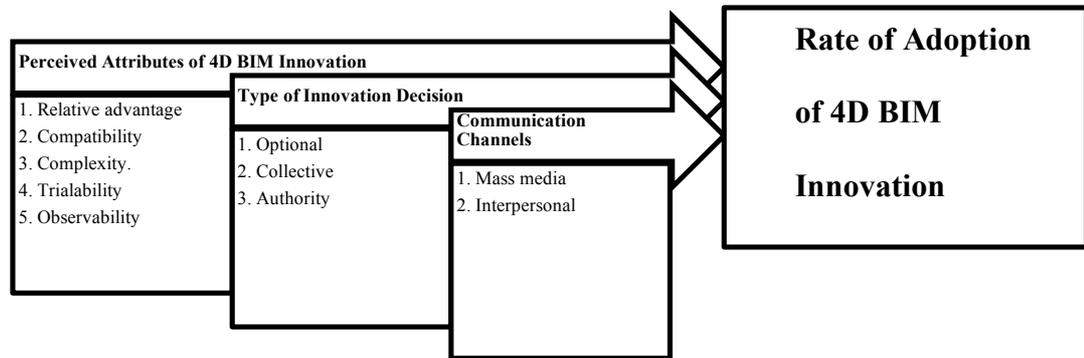

Figure 2: Variables determining the rate of 4D BIM innovation adoption. Adapted from Rogers (2003)

Independent diffusion variables used in the research design

The perceived attributes of an innovation

Rogers (2003) describes how individuals differing perceptions of an innovation's characteristics can directly affect its adoption rates. The perceived attributes of an innovation therefore help explain these rates of adoption.

1. *Relative advantage* is defined as "*the degree to which an innovation is perceived as better than the idea that it supersedes*" (Rogers, 2003). It is important to stress that it is the perception of any advantage that is held by the individual in relation to the existing idea which is of the most importance, rather than any actual

advantage that could be objectively measured. Diffusion theory holds that the more favourable the perceptions of an innovation's advantage, the greater the increase in its adoption rate. In the questionnaire survey, various functions of traditional construction planning practice and process were identified from a review of the wider construction planning literature, and for each of these, the respondents were required to assess the *relative advantages* of 4D BIM over traditional approaches:

- The functions of construction planning practice identified and used in the questionnaire were: *work winning; design interrogation; planning construction methods; visualising the construction process; facilitating understanding of the construction process; validating the time schedule; location based planning; progress reporting; site layout planning (positions); logistics planning (movements); communicating working space;* and *safety planning.*

- The elements of the construction planning process identified and used in the questionnaire were: *gathering information; identifying activities; assessing activity durations; planning the logical dependencies; planning the construction sequence; communicating the construction plan;* and *communicating project timescales.*

2. *Compatibility* is concerned with consistency of a potential adopters' experience, needs and values. Diffusion theory holds that innovations that are incompatible with existing infrastructures will not diffuse as rapidly as innovations that are compatible with such infrastructures. In the questionnaire, research respondents

were asked to consider whether the use of 4D BIM is compatible with their current practice of construction planning.

3. *Complexity* is concerned with perceptions of relative difficulty of use. Diffusion theory suggests that ease of comprehension by potential adopters aids the adoption rate. In the questionnaire survey respondents were asked to consider whether the 4D BIM planning practices would be difficult to learn and difficult to understand.

4. *Trialability* is concerned with the opportunity to experiment and use an innovation on a limited basis. Diffusion theory asserts that innovations that can be trialled without commitment are more readily adopted. In the questionnaire, research respondents we asked to consider if 4D BIM methods would have to be experimented with before using to plan real construction work.

5. *Observability* is concerned with visibility of the results of an innovation. Diffusion theory maintains that innovations that are more visible, or have visible positive results are adopted more readily. In the questionnaire, research respondents were asked to identify the impact that 4D BIM has on construction planning effectiveness.

To summarise, Rogers' (2003) view of the influence of the perceived attributes of an innovation is that *"Innovations that are perceived by individuals as having greater relative advantage, compatibility, trialability, and observability and less complexity will be adopted more rapidly than other innovations".* It is proposed therefore, that

these are especially appropriate for explaining the rate of adoption of an innovation such as 4D BIM and as such, they formed part of the questionnaire survey.

Communication channels.

Diffusion theory also considers that 'communication channels' may impact upon the rate of adoption of an innovation. Rogers (2003) makes the distinction between the originating 'source' of a communication and the 'channel' through which it is sent. He categorises communication channels as 'external' mass media communication channels and 'internal' interpersonal communication channels and makes the point that external mass media communication channels (print media, broadcast media, new online media) are able to quickly reach bigger audiences than internal interpersonal channels, thus accelerating the dissemination of information, understanding and comprehension. External channels are more important at the *knowledge stage* of the innovation-diffusion process, whereas internal channels are more important at the *persuasion stage* of the process as they involve two-way dynamic face-to-face exchanges of information which help decrease resistance to adoption and secure greater favourable attitudes toward the innovation. Furthermore, Rogers' theory asserts that adopter categories of *innovators* and *early adopters* are more susceptible to external communication channels whereas internal communication channels are more favourable for the *late adopters* and *laggards*. Interpersonal communication is particularly useful for innovation diffusion if the information transfer is truly internal - that is it is between near-peers, with someone from within the interpersonal network of a potential adopter rather than with external experts (Rogers, 2003).

In this research, the issue of communication channels was approached in a manner consistent with classic diffusion theory. Respondents were asked to select their preferences between external and internal sources, for obtaining of information about 4D BIM. Respondents were also asked to identify which of these sources would have the biggest impact on their own personal adoption or rejection decision of 4D BIM.

Classification of adopt-reject decisions

Innovation adoption/rejection decisions can be made either by individual or organisational decision-making units. Within the construction industry, it is more likely that decisions to adopt or reject an innovation are taken by a number of individuals or a group, rather than unilaterally. Larger companies may have to make a strategic decision to adopt an innovation, before any individual working for that organisation can then subsequently adopted it. Smaller enterprises may be more flexible with decisions taken by appropriate individuals. There is a need then to understand the types of innovation decision that can be made. Within diffusion theory, these types are:

1. Optional innovation decisions: made by individuals regardless of decisions made by other persons within the social system.

2. Collective innovation decisions: made in consensus with other persons within the social system (e.g. committee decisions)

3. Authority innovation decisions: made by a single person or small handful of people (e.g. Company directors) who possess the power to command the others within the social system to comply with their decision.

In addition, sequential combinations of any of the above decision types can also be made. These can be considered as 'contingent decisions'. In this research, the questionnaire provided a brief description of these three main classifications of decision-making and required respondents to place any innovation-adoption or -rejection decision into one of these categories. If no decision had yet been made, respondents were also asked to explain which type of decision would be likely to be made in adopting or rejecting 4D BIM.

Findings

Organisational characteristics

Demographic questions were asked to establish some information about the respondents and the types of organisations in which they worked. A profile of the research participants is presented in Table 2.

Table 2: Profile of survey respondents

	N	Frequency	%	Range	Minimum	Maximum	Mean	Std. Dev
Gender	97		100.0					
- *Male*		*86*	*88.7*					
- *Female*		*11*	*11.3*					
Age	97			46	22	68	40.2	10.7
Current Job Function	97		100.0					
- *Management Professional*		*47*	*48.5*					
- *Design Professional*		*5*	*5.2*					
- *Technical Specialist*		*45*	*46.4*					
Job level	97		100.0					
- *Upper Management (Strategy responsibility)*		*23*	*23.7*					
- *Middle Management (Tactical responsibility)*		*40*	*41.2*					
- *Lower Management (Day to day running)*		*34*	*35.1*					

	N	%	Range	Min	Max	Mean	Std
Number of years worked in the construction industry	97		47	1	48	17.9	11.6
Year started working in the construction industry	97		45	1969	2014	1996.7	11.7
Company Size (number of employees)	97	100.0					
- *Small (1-49)*			*19*	*19.6*			
- *Medium (50-249)*			*16*	*16.5*			
- *Large (250+)*			*62*	*63.9*			
Year company established	97		166	1848	2014	1951.9	50.6

Several questions related to company size and organisational BIM maturity. Q9 required the respondent to reveal the size of the company that they currently worked for (as measured by number of employees rather than by financial measures such as profit or turnover). The majority of respondents (63.9%; n = 62) identified themselves as working for a large company (250+ employees); 19.6% (n = 19) described themselves as working for a small company (1-49 employees); and the remaining 16.5% (n = 16) worked for medium-size enterprises. In Q11 the respondents' perception of their organisation's BIM maturity was assessed by

reproducing the simple definitions of various BIM maturity levels explained on the NBS website (NBS, 2014) and asking the respondent to identify the current BIM maturity level of their company. In response, 44.3% (n = 43) assessed their companies' BIM maturity at Level 2, and 34.0% (n = 33) at Level 1; 11.3% (n = 11) assessed their companies' BIM maturity at Level 3 and 10.3% (n = 10) at Level 0.

Inferential analysis was undertaken in order to explore statistical associations in the relationship between company size and organisational BIM Maturity, with appropriate null (H_0) and alternative (H_A) hypotheses formulated as follows:

- H_0: There is no relationship between company size and organisational BIM Maturity.
- H_A: There is a relationship between company size and organisational BIM Maturity.

In this test, all 97 responses were usable. Conditions for X^2 were not met as two cells had expected counts of less than 5, therefore a Fisher's Exact Test was used. This gave a test statistic of .001 allowing H_0 to be rejected in favour of H_A, i.e.: *there is a relationship between company size compared against organisational BIM Maturity*. Further examination of the largest proportion (42.3%) of data produced in the cross-tabulation about this relationship appears to suggest that larger companies are more likely to have greater organisational BIM maturity.

Rate of Adoption

In response to Q14, '*Do you currently use 4D BIM in your construction planning practices?*' 51.5% (n = 50) of the total respondents confirmed that they did. Respondents who answered 'NO' were then asked Q16 '*Are you aware of anyone in your organisation who currently uses 4D BIM in their construction planning practices?*' 11.3% of the total respondents (n = 11) confirmed use. Combining these positive responses implies that 62.8% (n = 61) of respondents use 4D BIM themselves or are aware of someone in their organisation who does. The remaining 37.2% (n = 36) do not use 4D BIM and are not aware of anyone in their organisation who does. Focussing only on respondents who self-identified as adopters, these were asked separately, in which year they first became aware of 4D BIM (Q12) and in which year they adopted 4D BIM innovation in their construction planning practices for the first time (Q15). The earliest year of awareness was 1998, with the mean year being 2009, and the median 2011. The majority of the responses fell within the date range of 2002 – 2015. The earliest year of adoption was 2002, the mean 2011, and the median 2013. [*Note: For those only reporting upon awareness of others in their organisation that have adopted 4D BIM, the earliest year of adoption was assumed to be 2010, the mean year was 2012 and the median year was 2013*].

Focussing again on self-identified adopters, a comparison was made between the year of first awareness and the year of first use (adoption). The Pearson Correlation coefficient for these two measures is .764 which, according to (Bryman and Cramer, 2011) can be described as *a "strong positive relationship"* and the 2-tailed statistic is .000, which is significant at the 0.01 level. The coefficient of determination (R2

Statistic) is 0.583 as shown in Figure 3, which means that more than half (58.3%) of the variance in the timing of first adoption can be attributed to the timing of first awareness.
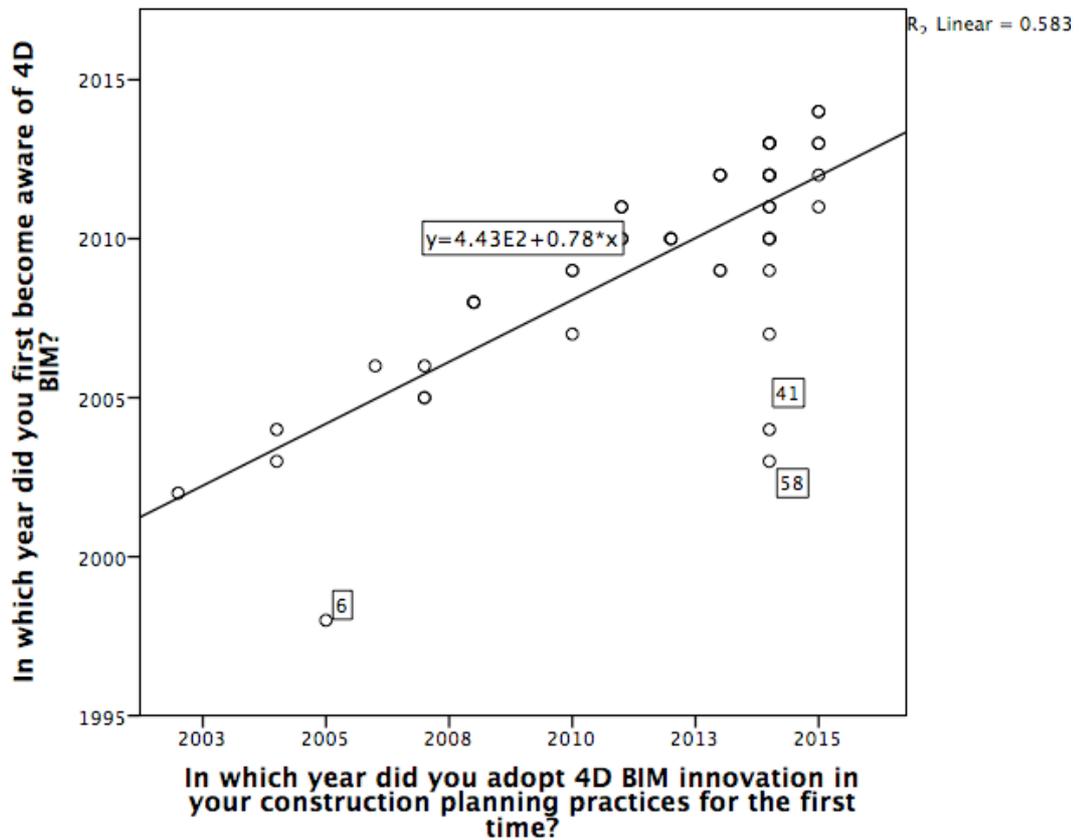

Figure 3: Year of awareness vs. year of adoption for respondents self-identifying as adopters

The data also revealed a handful of interesting outliers, all of whom worked for large contracting organisations of 250+ employees. The earliest recorded awareness of 4D BIM in this sample was respondent 6 who first became aware in 1998 but did not adopt until 2005 and then only because of a company (authority) decision. The longest period between awareness and adoption - a lag of 11 years - was observed in respondent 58 who first became aware in 2003 but did not adopt until 2014. This adoption was described as a 'collective decision'. Respondent 41 is another outlier

who first became aware in 2004 but did not adopt until 2014, a lag of 10 years, and whose adoption was described as an 'authority decision'. Apart from these outliers, the usual time lag recorded between awareness and adoption was generally between 2.38 – 3.00 years (28.5 - 36.0 months).

Sufficient data were available to permit a separate comparison of personal use of 4D BIM and (in turn) *company size* and *organisational BIM Maturity*. Competing hypotheses for the first test were:

- **H_0:** There is no relationship between company size and personal use of 4D BIM.
- **H_A:** There is a relationship between company size and personal use of 4D BIM.

In this test, all 97 cases were used. Conditions for Chi-Square (X^2) were met and a test statistic of .002 resulted, meaning that H_0 could be rejected in favour of H_A namely that *There is a relationship between company size and personal use of 4D BIM innovation.* Examination of the largest proportion (39.2%) of data produced in the cross-tabulation about this relationship suggests that there is more likely to be personal use of 4D BIM innovation within larger companies of 250 employees+.

Competing hypotheses for the further test were also formulated:

- **H₀:** There is no relationship between organisational BIM maturity compared against personal use of 4D BIM.

- **Hₐ:** There is a relationship between organisational BIM maturity compared against personal use of 4D BIM.

In this test, all 97 cases could be used. Conditions for Chi-Square (X^2) were not met as one cell had expected counts of less than 5; therefore, a Fisher's Exact Test was used. This gave a test statistic of .000 meaning that H_0 could be rejected in favour of H_A, that is: *There is a relationship between organisational BIM maturity compared against personal use of 4D BIM Innovation.* The implication being that higher personal usage of 4D BIM will occur within organisations that are considered to have higher levels of BIM maturity.

Decision Types

Several questions focussed on decision types. Q44 asked the respondent to '*confirm if a* [subsequent] *decision has been made to adopt or reject the use of 4D BIM for the planning of construction work*'. Depending upon this response Q45/46 asked which type of decision was made to adopt/reject 4D BIM. As a result, 67.0% of respondents (n = 65) confirmed that a decision had been made to adopt 4D BIM for the planning of construction work, with 1.0% (n = 1) of respondents confirming that a decision had been made to reject 4D BIM. The remaining 32.0% (n = 31) of respondents selected the *undecided/no decision made* option. Following this Q45 asked '*If possible, please explain which type of decision was made to adopt 4D BIM*'. An explanation, as outlined above, was provided about the three available response options: namely, *Optional*, *Collective* and *Authority* -decisions. Taking the

subset of 65 respondents who confirmed that an *adopt* decision had been made, the most frequent type of decision, recorded by 46.2% (n = 30), was an 'authority-type' decision The next most frequent, with 33.8% (n = 22) of responses, was the 'collective-type' decision, and the least frequent was the 'optional-type' decision, with 20% (n = 13) of respondents reported this option (*note 'valid percentages' used for this question so that the responses from the 65 respondents totalled 100%*). In Q46 respondents were asked '*If possible, please explain which type of decision was made to reject 4D BIM*', and the sole respondent who advised that a definite reject decision had been made, confirmed that this had been a 'collective-type' decision.

Perceived attributes: Relative advantages

In this section we briefly examine the perceived relative advantages of 4D BIM in two distinct aspects of construction planning. These are (i) *construction planning functions* (i.e. the required outcomes of the planning process) and (ii) *construction planning processes* (i.e. the things that planners do when they plan).

Relative advantages of 4D BIM in construction planning functions

A series of 5-point Likert scales was used to measure strength of agreement where 4D BIM could offer a relative advantage against the various functions of construction planning practice identified within the research methods section. In order to rank, by function, the relative advantage offered by the use of 4D BIM over traditional methods a Relative Importance Index (RII) was calculated for each. The use of RII to illustrate the ranking of responses is relatively commonplace in

construction management literature (see for example, Gündüz et al., 2012, in the context of factors causing project delays). The RII was calculated as shown in Equation 1, as shown.

$$RII = \frac{\sum W}{A \times N} \qquad \text{Equation 1}$$

Where:

W is the weight given to each factor by respondents (from 1 to 5)

A is the highest weight (i.e. always 5) and

N is the number of responses

Table 3: Perceived Relative Importance (RII) and ranking of use of 4D BIM in 12 identified planning functions

Functions	N	∑ W	A x N	RII	Rank
Visualising the construction process	97	424	485	0.874	1
Facilitating understanding of the construction process	97	414	485	0.854	2
Logistics planning (movements)	97	401	485	0.827	3
Communicating working space	97	399	485	0.823	4
Site layout planning (positions)	97	398	485	0.821	5
Design interrogation	97	396	485	0.816	6
Planning construction methods	97	394	485	0.812	7
Work winning	97	379	485	0.781	8
Validating the time schedule	97	378	485	0.779	9
Safety planning	97	373	485	0.769	10
Location based planning	97	369	485	0.761	11=

	N	∑ W	A x N	RII	Rank
Progress reporting	97	369	485	0.761	11=

It is clear from Table 3 that most of the highest ranked advantages of 4D BIM, as compared with current traditional approaches (*visualising the construction process, facilitating understanding of the construction process, communicating working space*) relate to its potential to alleviate the problems of communication and understanding that were identified earlier. Functions that represented the 'internal workings' of the planning process (*validating the time schedule, location based planning, progress reporting*) were the lowest ranked.

Relative advantages of 4D BIM against construction planning process

The same method of analysis was used to assess the relative advantages of 4D BIM against the elements of the construction planning process also identified in the research methods section. Again, the RII, calculated as above, measures the relative importance of the use of 4D BIM in each of the above construction planning processes, as shown in Table 4.

Table 4: Perceived Relative Importance (RII) and ranking of use of 4D BIM in 7 identified planning processes

Processes	N	∑ W	A x N	RII	Rank
Communicating the construction plan	97	418	485	0.862	1
Planning the construction sequence	97	387	485	0.798	2

Planning the logical dependencies	97	380	485	0.784	3
Communicating project timescales	97	370	485	0.763	4
Identifying activities	97	364	485	0.751	5
Gathering information	97	342	485	0.705	6
Assessing activity durations	97	335	485	0.691	7

The processes listed in Table 4 relate to what is described above as 'internal workings' of the planning process, i.e. 'the things that planners do'. Again, the highest ranked item, by a considerable margin. related to the planner's task of '*Communicating the construction plan*'.

Perceived attributes: Compatibility, complexity, trialability and observability

Statements were posed relating to the aspects of *compatibility, complexity, trialability* and *observability*, and strength of agreement was again measured using 5-point Likert scales. To measure compatibility, Q38 stated '*the use of 4D BIM is compatible with our current practice of construction planning*'. Diffusion theory asserts that innovations that are compatible with existing infrastructures will diffuse more rapidly than those innovations that are not compatible with such infrastructures. The statement met with 61.9% (n = 60) agreement, with the mean response being 3.58 and the median response being 4.00 out of 5.00. Complexity is considered to be a barrier to innovation diffusion (and thus to 4D BIM adoption). Several expressions of complexity were presented and the direction of response was fairly consistent. To Q39 ('*4D BIM methods would be difficult to learn*') only 23.7%

(n = 23) of participants registered agreement, with the mean response being 2.84 and the median response being 3.00 out of 5.00. In response to Q40 ('*4D BIM methods would be difficult for planners to understand*') there was again a low rate of agreement, with only 14.4% (n = 14) of the participants agreeing, and the mean response being 2.47 and the median response being 2.00 out of 5.00. There was another relatively low rate of agreement to Q41 ('*The training required in order to learn 4D BIM methods would be complicated*') with 30.9% (n = 30) in agreement. The mean response was 2.86 and the median response was 3.00 out of 5.00. As diffusion theory considers that ease of comprehension by potential adopters aids adoption rate, these lower scores can be considered to be positive in terms of the avoidance of potential barriers to the adoption of 4D BIM.

To measure 'trialability' Q42 stated '*4D BIM methods would have to be experimented with before using to plan real construction work*'. Diffusion theory states that innovations that cannot be trialled without commitment are less readily adopted. There was 58.7% (n = 57) agreement with this statement, with the mean response being 3.46 and the median response being 4.00 out of 5.00.

The final question concerning the perceived attributes of 4D BIM innovation related to '*observability*'. Diffusion theory holds that innovations that are more visible, or have visible positive results are adopted more readily. Accordingly, Q42 was worded '*It is easy to see the impact that 4D BIM has on construction planning effectiveness*' and 74.2% (n = 72) of the participants were in agreement, with the mean response being 3.80 and the median response being 4.00 out of 5.00.

Communication channels

Respondents were asked two questions in relation to communication channels with the same two response options ('*External Sources, i.e.: Mass media including websites, journals, magazines; government*' and '*Internal sources i.e.: Colleagues, peers, workmates or interpersonal networks*') provided for each question. In Q47 respondents were asked '*Please select your preference for obtaining information about 4D BIM Innovation*'. This is important at the knowledge stage of the innovation-decision process, and 53.6% (n = 52) of respondents identified 'external sources' as being their preference for obtaining of information about 4D BIM, with the remaining 46.4% (n = 45) of respondents identifying 'internal sources' as being their preference.

Focusing on the 'persuasion stage' of the innovation-decision process, Q48 asked '*which of the following has had/would have the biggest impact on your own personal decision to adopt or reject the use of 4D BIM Innovation*'). This time 64.9% (n = 63) of respondents identified that *internal sources* had/would have the biggest impact on their own personal decision in relation to their adoption or rejection of 4D BIM, with the remaining 35.1% (n = 34) of respondents, identifying *external sources* would have the greater influence. These results allowed competing hypotheses to be formed and tested:

- **H$_0$:** *There is no relationship between a preferred source of information about 4D BIM and the impact of such influences in any adoption or rejection decision.*

- **H$_A$:** *There is a relationship between a preferred source of information about 4D BIM and the impact of such influences in any adoption or rejection decision.*

Conditions for a Chi-Square (X^2) test of independence were met, and all 97 cases could be used. A test statistic of .000 was given meaning that H$_0$ could be rejected in favour of H$_A$: *There is a relationship between a preferred source of information about 4D BIM and the impact of such influences in any adoption or rejection decision.* A review of the cross-tabulation results confirmed the strongest association (43.3%) was between internal sources for information preference and internal influences for impact upon decision-making. This finding, that construction professionals prefer to obtain innovation information from within their own interpersonal networks, is in opposition to one of Rogers' (2003) key generalizations (5-13) that "*mass media channels are relatively more important at the knowledge stage and interpersonal channels are relatively more important at the persuasion stage in the innovation-decision process*".

Which variables determine the rate of 4D BIM adoption?

The time lag for 4D BIM adoption, that is, between first awareness and use, was found to be between 2.38 – 3.00 years (28.5 - 36.0 months). To further explain the rate of adoption, we return to the independent variables incorporated in the research design as diffusion predictors. Each of these independent variables can be tested against the adoption of 4D BIM, which was measured by way of a simple categorical

YES/NO question in Q14 for '*Do you currently use 4D BIM in your construction planning practices?*' where 51.5% (n = 50) of the total respondents confirmed use. Ordinal variables were used for the '*perceived attribute*' questions and categorical variables were used for the '*decision type*' and '*communication channels*' questions, meaning that Chi-square or Fishers Exact tests could be used to test for the following possible associations:

- Relative advantages of 4D BIM *against* use of 4D BIM.

- Compatibility of 4D BIM *against* use of 4D BIM.

- Complexity of 4D BIM *against* use of 4D BIM.

- Trialability of 4D BIM *against* use of 4D BIM.

- Observability of 4D BIM *against* use of 4D BIM.

- Types of innovation adoption decisions taken *against* use of 4D BIM.

- Communication channel preferences *against* use of 4D BIM.

This required 28 separate tests. In each test, appropriate null (H_0) and alternative (H_A) hypotheses were formulated. Where no significant associations were found the results of the tests are not detailed, however among them it is worth noting that a Fishers Exact Test provided a statistic of .079 (slightly outside the margins of significance) for the *relative advantage of using 4D BIM for communicating the construction plan*.

Significant associations were found in the tests of association involving *compatibility* and *trialability* as a means of explaining the rate of 4D BIM adoption. The competing hypotheses for the test of compatibility were:

- **H$_0$**: There is no relationship between how compatible 4D BIM is with the current practice of construction planning, compared *against* the personal adoption and use of 4D BIM

- **H$_A$**: There is a relationship between how compatible 4D BIM is with the current practice of construction planning, compared *against* the personal adoption and use of 4D BIM

In this test, all 97 cases could be used. Conditions for X^2 were not met as two cells had expected counts of less than 5; therefore, a Fisher's Exact Test was used. This gave a test statistic of .026 which meant that H$_0$ could be rejected in favour of H$_A$, that: *There is a relationship between how compatible 4D BIM is with the current practice of construction planning compared against the personal adoption and use of 4D BIM.* Exploration of the data produced in the cross-tabulation about this relationship suggests that whilst both adopters and non-adopters alike consider 4D BIM compatible with current planning practices (61.9%), only 5.2% of those who have adopted 4D BIM consider it to be incompatible with current planning practices.

The second test concerns the trialability of 4D BIM against use of 4D BIM. The competing hypotheses were:

- **H$_0$**: There is no relationship between a need to experiment with 4D BIM prior to using it to plan real construction work, compared *against* the personal adoption and use of 4D BIM

- **H$_A$**: There is a relationship between a need to experiment with 4D BIM prior to using it to plan real construction work, compared *against* the personal adoption and use of 4D BIM

In this test, all 97 cases could be used. Conditions for X^2 were not met as two cells had expected counts of less than 5; therefore, a Fisher's Exact Test was used. This gave a test statistic of .005 which meant that H_0 could be rejected in favour of H_A, i.e. that *There is a relationship between a need to experiment with 4D BIM prior to using it to plan real construction work compared against personal adoption and use of 4D BIM.* Analysis of the data produced in the cross-tabulation about this relationship appears to suggest that whilst adopters are equally likely to agree or disagree with the need for experimenting or trialling 4D BIM (i.e. there is no real trend in this category), persons who have not yet adopted it feel much more strongly that there is a need to trial 4D BIM before using it to plan real construction work (35.0%).

Conclusions

Innovation Diffusion Theory (IDT) considers how, why, and at what rate, new ideas and technology spread. The aim of this survey was to investigate the diffusion of 4D BIM within UK construction planning practice. In doing so, the work provides further validation of the applicability of IDT for studying innovation diffusion in, and around, the Architecture Engineering and Construction AEC industry. In designing the survey, key variables from classic diffusion theory were used alongside constructs derived from the literature on construction planning. The research aimed to explore and explain the rate of adoption of 4D BIM, and used statistical analysis of the results to demonstrate how first adoption of 4D BIM is related to the timing of first awareness of the innovation. Results indicate that adoption of 4D BIM for the planning of construction projects, has a typical time lag of 2.38 – 3.00 years between awareness and first use. Decisions to adopt 4D BIM are

typically authority-type decisions made by organisational upper management and exploration of the data at individual case level also revealed situations where, despite instances of early innovation awareness, the absence of authority-type adoption decisions, has slowed diffusion. Many construction planning functions and stages of the construction planning process were considered to be more effective using 4D BIM than current construction planning practices. A particular example was the relative advantage of the use of 4D BIM for communicating the construction plan. High complexity and lack of observability, compatibility and opportunities for trialling are all theoretical barriers to the diffusion of innovations. Whilst complexity and observability remain important aspects of any innovation adoption, in the case of 4D BIM adoption, concerns over compatibility and opportunities for trialling the innovation appear to be the more prominent factors.

The study offers a number of implications for practice. First, in order for 4D BIM to diffuse more rapidly, potential adopters have to be convinced that whilst 4D BIM is a technological process-based innovation, it is also a 'modular innovation' (Slaughter, 1998, 2000) which may produce significant improvements but does not require alteration of other system level components and therefore is compatible with existing planning practices. Secondly, it is advantageous if the innovation can be trialled in a safe environment prior to use on a live construction project. Finally, at very least, there was a consensus that the relative advantage of being able to communicate the construction plan using 4D methods rather than traditional formats mean that this innovation is worth adopting.

There are limitations to this study, most prominently in the manner in which the dependent variable of adoption was measured (via a simple categorical YES/NO

response option). This means that the research team have not been able to distinguish between different levels of 4D BIM adoption in use. For example, in some organisations 4D BIM may merely have been adopted for purposes of visualisation and work winning efforts, where in other organisations perhaps use of the innovation was discontinued after limited use. Despite these limitations, the findings of this study do provide a basis for future research efforts. For example, studies that provided rich qualitative data on any of the remaining classic diffusion variables would be of value. Further studies could involve:

- Interviews around the 4D BIM *innovation-decision process*, which is concerned with aspects of innovation *Knowledge; Persuasion; Decision; Implementation* and *Confirmation*;
- Observations of key actors from within the social system such as *Opinion Leaders,* and *Change Agents;* and
- Case studies exploring the *consequences* of 4D BIM innovation adoption.

Finally, in the light of the finding of this study, that information preferences and adoption/rejection decisions are more likely to be influenced by internal than external factors, Rogers' (2003) assertion that *"interpersonal communication with near peers drives the diffusion process"* would merit closer in-depth exploration.

References

Barnlund, C. (2008), "A transactional model of communication", in Mortensen, C. (Ed.),*Communication theory*, Transaction, New Brunswick, New Jersey, 2nded.

Berlo, D. (1960), *The process of communication*, Holt, Rinehart, & Winston., New York, New York.

Bryman, A. and Cramer, D. (2011), *Quantitative Data Analysis with IBM SPSS 17,*

18 & 19, Analysis, Routledge, Hove, Vol. 1st editio, doi:10.4324/9780203471548.

Buchmann-Slorup, R. and Andersson, N. (2010), "BIM-based scheduling of construction–a comparative analysis of prevailing and BIM-based scheduling processes", *Proceedings of the CIB W78 2010: 27th International Conference*, Cairo, pp. 16–18.

Crotty, R. (2012), *The Impact of Building Information Modelling: Transforming Construction*, SPON Press, Oxon.

Cullen, J. and Nankervis, C. (1985), "Overcoming the luddite factor: some behavioural aspects of the field supervisor's role in construction planning", *International Journal of Project Management*, Vol. 3 No. 3, pp. 133–140.

Dawood, N. (2010), "Development of 4D-based performance indicators in construction industry", *Engineering, Construction and Architectural Management*, Vol. 17 No. 2, pp. 210–230.

Dodgson, M. and Gann, D. (2010), *Innovation*, A very short introduction, Oxford University Press, Oxford, available at: http://capitadiscovery.co.uk/northumbria-ac/items/1482707.

Easterby-Smith, M., Thorpe, R. and Jackson, P. (2008), *Management Research*, SAGE, London, 3rded.

Emmitt, S. (2010), *Managing interdisciplinary projects: a primer for architecture, engineering and construction*, Spon Press, Abingdon, Oxon.

Fellows, R. and Liu, A. (2008), *Research methods for construction*, Wiley-Blackwell, West Sussex, 3rded., available at: http://www.loc.gov/catdir/toc/ecip088/2008002534.html.

Gledson, B. (2015), "Investigating the diffusion of 4D BIM Innovation", in Raiden, A. and Aboagye-Nimo, E. (Eds.),*Proceedings 31st Annual ARCOM Conference*, ARCOM, Lincoln, UK, pp. 641–650.

Gledson, B.J. (2016), "Hybrid project delivery processes observed in constructor BIM innovation adoption", *Construction Innovation*, Emerald, Vol. 16 No. 2, pp. 229–246.

Gledson, B.J. and Greenwood, D. (2014), "The implementation and use of 4D BIM and Virtual Construction", in Raiden, A.B. and Aboagye-Nimo, E. (Eds.),*Proceedings 30th Annual ARCOM Conference*, ARCOM, Portsmouth, UK 1-3rd September 2014, pp. 673–682.

Gledson, B.J. and Greenwood, D.J. (2016), "Surveying the extent and use of 4D BIM in the UK", *Journal of Information Technology in Construction (ITcon)*, Vol. 21 No. April, pp. 57–71.

González, P., González, V., Molenaar, K. and Orozco, F. (2013), "Analysis of causes of delay and time performance in construction projects", *Journal of Construction Engineering and Management*, American Society of Civil Engineers, Vol. 140 No. 1, p. 4013027.

Gorse, C. and Emmitt, S. (2007), "Communication behaviour during management and design team meetings: a comparison of group interaction", *Construction*

Management and Economics, Vol. 25 No. 11, pp. 1197–1213.

Gorse, C. and Emmitt, S. (2009), "Informal interaction in construction progress meetings", *Construction Management and Economics*, Vol. 27 No. 10, pp. 983–993.

Greenwood, D. and Gledson, B.J. (2012), "The efficient scheduling of resources in engineering construction projects : reflections on a case study from Iran", *Construction Management and Economics*, Vol. 30 No. 8, pp. 687–695.

Hartmann, T. and Fischer, M. (2007), "Supporting the constructability review with 3D/4D models", *Building Research & Information*, Vol. 35 No. 1, pp. 70–80.

Hartmann, T., Gao, J. and Fischer, M. (2008), "Areas of Application for 3D and 4D Models", *Journal of Construction Engineering and management*, Vol. 134 No. 10, pp. 776–785.

Hartmann, T. and Vossebeld, N. (2013), "A semiotic framework to understand how signs in construction process simulations convey information", *Advanced Engineering Informatics*, Elsevier Ltd, Vol. 27 No. 3, pp. 378–385.

Heesom, D. and Mahdjoubi, L. (2004), "Trends of 4D CAD applications for construction planning", *Construction Management and Economics*, Vol. 22 No. 2, pp. 171–182.

HM Government. (2011), *Government Construction Strategy*, London.

HM Government. (2013), *Construction 2025. Industrial Strategy: government and industry in partnership*, London, available at: http://www.bis.gov.uk/assets/biscore/innovation/docs/b/12-1327-building-information-modelling.pdf.

Hosseini, M.R., Chileshe, N., Zuo, J. and Baroudi, B. (2015), "Adopting global virtual engineering teams in AEC Projects: A qualitative metaanalysis of innovation diffusion studies", *Construction Innovation: Information, Process, Management*, Vol. 15 No. 2, pp. 151–179.

Kale, S. and Arditi, D. (2010), "Innovation Diffusion Modeling in the Construction Industry", *Journal of Construction Engineering and Management*, Vol. 136 No. 3, pp. 329–340.

Kassem, M., Dawood, N. and Chavada, R. (2015), "Construction workspace management within an Industry Foundation Class-Compliant 4D tool", *Automation in Construction*, Elsevier B.V., Vol. 52, pp. 42–58.

Kim, C., Kim, B. and Kim, H. (2013), "4D CAD model updating using image processing-based construction progress monitoring", *Automation in Construction*, Elsevier B.V., Vol. 35, pp. 44–52.

Kim, H., Anderson, K., Lee, S. and Hildreth, J. (2013), "Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology", *Automation in Construction*, Elsevier B.V., Vol. 35, pp. 285–295.

Koo, B. and Fischer, M. (2000), "Feasibility Study of 4D CAD in Commercial Construction", *Journal of Construction Engineering and Management*, Vol. 126 No. 4, pp. 251–260.

Larsen, J.K., Shen, G.Q., Lindhard, S.M. and Brunoe, T.D. (2015), "Factors Affecting Schedule Delay, Cost Overrun, and Quality Level in Public Construction Projects", *Journal of Management in Engineering*, American Society of Civil Engineers, Vol. 32 No. 1, p. 4015032.

Li, H., Guo, H.L., Skitmore, M., Huang, T., Chan, K. and Chan, G. (2011), "Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong", *Construction Management and Economics*, Vol. 29 No. 3, pp. 233–245.

Li, H., Huang, T., Kong, C.W.W., Guo, H.L.L., Baldwin, A., Chan, N. and Wong, J. (2008), "Integrating design and construction through virtual prototyping", *Automation in Construction*, Vol. 17 No. 8, pp. 915–922.

Liston, K., Fischer, M. and Winograd, T. (2001), "Focused sharing of information for multidisciplinary decision making by project teams", *ITCon*, Vol. 6, pp. 69–82.

Love, P.E.D., Sing, C.-P., Wang, X., Edwards, D.J. and Odeyinka, H. (2013), "Probability distribution fitting of schedule overruns in construction projects", *Journal of the Operational Research Society*, Vol. 64 No. 8, pp. 1231–1247.

Mahalingam, A., Kashyap, R. and Mahajan, C. (2010), "An evaluation of the applicability of 4D CAD on construction projects", *Automation in Construction*, Elsevier B.V., Vol. 19 No. 2, pp. 148–159.

Moore, M. (1993), "Theory of transactional distance", in Keegan, D. (Ed.),*Theoretical Principles of Distance Education*, Routledge, New York, N.Y.

Myers, D. (2013), *Construction Economics: A New Approach*, Routledge, Oxon, 3rded., available at: http://www.amazon.com/Construction-Economics-A-New-Approach/dp/0415527791 (accessed 5 November 2013).

Olaniran, O.J., Love, P.E.D., Edwards, D., Olatunji, O.A. and Matthews, J. (2015), "Cost Overruns in Hydrocarbon Megaprojects: A Critical Review and Implications for Research", *Project Management Journal*, Wiley Periodicals, Inc., Vol. 46 No. 6, pp. 126–138.

Olde Scholtenhuis, L.L., Hartmann, T. and Dorée, A.G. (2016), "4D CAD Based Method for Supporting Coordination of Urban Subsurface Utility Projects", *Automation in Construction*, Elsevier B.V., Vol. 62, pp. 66–77.

Reichstein, T., Salter, A.J. and Gann, D.M. (2005), "Last among equals: a comparison of innovation in construction, services and manufacturing in the UK", *Construction Management and Economics*, Vol. 23 No. 6, pp. 631–644.

Rogers, E.. (2003), *Diffusion of Innovations*, Free Press, Simon & Schuster, New York, N.Y., 5thed.

Shannon, C. and Weaver, W. (1949), *The mathematical theory of communication*, University of Illinois Press, Urbana, Illinois.

Slaughter, E. (1998), "Models of Construction Innovation", *Journal of Construction Engineering and Management*, Vol. 124 No. 3, pp. 226–231.

Slaughter, E. (2000), "Implementation of construction innovations", *Building*

Research & Information, Vol. 28 No. 1, pp. 2–17.

Soetanto, R., Childs, M., Poh, P., Austin, S. and Hao, J. (2014), "Virtual collaborative learning for building design", *Proceedings of the ICE-Management, Procurement and Law*, Thomas Telford, Vol. 167 No. 1, pp. 25–34.

Trebbe, M., Hartmann, T. and Dorée, A. (2015), "4D CAD models to support the coordination of construction activities between contractors", *Automation in Construction*, Elsevier B.V., Vol. 49, pp. 83–91.

Turk, Ž. (2016), "Ten questions concerning building information modelling", *Building and Environment*, Vol. 107, pp. 274–284.

Wang, H.., Zhang, J., Chau, K.. and Anson, M. (2004), "4D dynamic management for construction planning and resource utilization", *Automation in Construction*, Vol. 13 No. 5, pp. 575–589.

Winch, G. and Kelsey, J. (2005), "What do construction project planners do?", *International Journal of Project Management*, Vol. 23 No. 2, pp. 141–149.