INVESTIGATING THE DIFFUSION OF 4D BIM INNOVATION

Barry Gledson[1]

Department of Mechanical and Construction Engineering, Northumbria University, Northumberland, UK

UK Government regularly applies challenging strategic targets to the construction industry, chief amongst these are requirements for more rapid project delivery processes and consistent improvements to the time predictability aspects of on-site construction delivery periods. Latest industry KPI data has revealed a recent increase across measures of time predictability, however more than half of UK construction projects continue to exceed agreed time schedules. The aim of this research was to investigate the diffusion of 4D BIM innovation as adoption of this innovation is seen as a potential solution in response to these targets of construction time predictability. Through purposive sampling, a quantitative survey was undertaken using an online questionnaire that measured 4D BIM innovation adoption using accepted diffusion research methods. These included an exploration of several perceived attributes including compatibility, complexity, observability and the relative advantages of 4D BIM innovation in comparison against conventional functions of construction planning and against stages of the construction planning processes. Descriptive and inferential analysis of the data addresses how the benefits are being realised and explore reasons for adoption or rejection decisions of this innovation. Results indicate an increasing rate of 4D BIM innovation adoption and reveal the typical time lag between awareness and first use.

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 2013 governmental strategy report (HM Government, 2013) where a ‘Vision for 2025’ presented requirements for 50% faster UK project delivery benchmarked against 2013 industry performance. Annual data had 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 with 42% of construction phases delivered on or before their original planned completion date (Gledson and Greenwood, 2014). The latest KPI data has identified increases across all measures of time predictability, however more than half of UK construction projects continue to exceed their agreed time schedules.

[1] barry.gledson@northumbria.ac.uk

Gledson, B (2015) Investigating the diffusion of 4D BIM innovation *In:* Raidén, A B and Aboagye-Nimo, E (Eds) *Procs 31st Annual ARCOM Conference*, 7-9 September 2015, Lincoln, UK, Association of Researchers in Construction Management, 641-650.

Table 1: Construction time predictability for years 2007 - 2013 - percentage of projects and phases delivered on time or better. Table adapted from Constructing Excellence (2014)

KPI	2007	2008	2009	2010	2011	2012	2013
Predictability Time: Project	58	45	45	43	45	34	45
Predictability Time: Design	58	58	53	69	51	48	52
Predictability Time: Construction	65	58	59	57	60	42	67

LITERATURE REVIEW

Conventional construction planning

Construction planning is required to determine project duration against which performance is measured. 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 standard solutions (Greenwood and Gledson, 2012). Construction programmes can suffer from systems complexity with the large volume of Tasks Per Programme (TPP) being one such indicator of complexity. This has been illustrated in previous research efforts where Liston, Fischer and Winograd, (2001) used a typical construction programme that contained 8000 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 multiple logical dependencies and different dependency types (such as Finish to Start; Start to Start; Start to Start with Lag) that are applied to each individual task, meaning that increases in the number of possible logical iterations also increase the complexity of the programme.

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 (Emmitt, 2010) containing multiple components set against a background of ‘noise’. 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 can consider that they have sent clear messages there always remains doubts of whether such messages have been received and processed as intended. Within literature various communication models have been developed including early simple linear Sender-Message-Channel-Receiver models (Shannon and Weaver, 1949; Berlo, 1960) and later Encode-Transmit-Receive-Decode, transactional models of communication (Barnlund, 2008) that recognised 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, use of 4D BIM can reduce this gap further.

Closing transaction distance through the diffusion of 4D BIM innovation

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 systematic review of innovation diffusion literature undertaken by Reza Hosseini *et al*., (2015) identified construction innovation core attributes: being new to the implementing institution(s); of a non-trivial change in nature; forecasting process related benefits; generating value to organisational strategic outcomes; providing competitive advantages; subject to much uncertainty and risk; and importing practices from outside of 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 get in the way of the message (Cullen and Nankervis, 1985). 4D planning involves making use of 4D BIM innovation 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 (Liston *et al*., 2001; Büchmann-Slorup and Andersson 2010) to analyse the construction schedule to assess its implementation (Koo and Fischer, 2000; Mahalingam, Kashyap and Mahajan, 2010; Trebbe, Hartmann and Dorée, 2015) and help reduce scheduling errors through plan interrogation and validation. 4D BIM innovation 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, Kashyap and Mahajan, 2010).

Problems of resistance and diffusion

Several researchers consider there to be an increase in the uptake of construction professionals using 4D BIM innovation (Hartmann, and Fischer, 2007; Hartmann, Gao, and Fischer, 2008; Trebbe, Hartmann and Dorée, 2015). Mahalingam, Kashyap, and Mahajan (2010) noted the gap between the theoretical benefits, of communication and operational efficiencies espoused within the literature, and actual use within industry and note that 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. One significant frustration for many practitioners is the challenges faced when changes in working processes are introduced, particularly in terms of having to learn new software, after years of gaining a particular expertise. Construction 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 of time synthesising their experiences over each project and Dodgson and Gann (2010) identify that such disruptive innovations are likely to disturb the delicate balance and the implicit social contracts that lie between organisations and their employees. Mahalingam, Kashyap, and Mahajan (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"*. Thus there is then a need to consider 4D BIM innovation from the perspective of innovation diffusion theory.

Previous research 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 (Gledson and Greenwood, 2014). 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 these opportunities for further research.

RESEARCH METHOD AND FINDINGS

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 to be an appropriate means of data collection and purposive sampling was employed. The survey was opened for in April 2014 and collected 80 full responses. An additional 51 partial responses were received although these were excluded from analysis due to their incompleteness. The 5 part questionnaire contained 49 questions which closely followed several of Rogers (2003) key variables, adapted in Figure 1 to determine the rate of innovation adoption: These included 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; types of innovation decisions made, and information regarding communication channels. Because of page limitations only summary results have been reported in this paper.

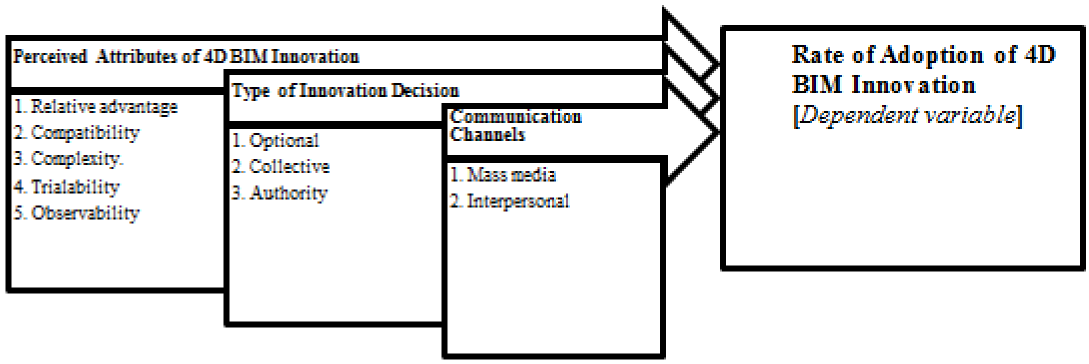

Figure 1: Variables determining the rate of 4D BIM innovation adoption. Adapted from Rogers (2003)

Findings

Rate of Adoption

In response to Q14 '*Do you currently use 4D BIM in your construction planning practices?*' 56.3% (n = 45) of the total respondents confirmed use. 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 = 9) confirmed use, meaning 67.6% (n = 54) of respondents use/are aware of someone in their organisation that uses 4D BIM innovation. The remaining 32.4% (n = 26) do not use and are not aware of anyone in their organisation that uses 4D BIM innovation. Focussing only on respondents who self identified as adopters, these were asked 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, the mean 2009 and the median 2010. 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, both the mean and median years were 2013*].

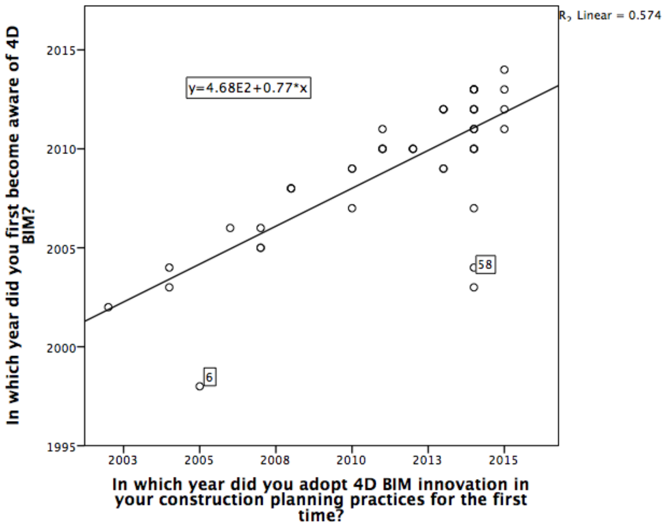

Figure 2: Year of awareness vs. year of adoption for respondents self identifying as adopters

The Pearson's Correlation for these two measures is .758 and the 2-tailed statistic is .000, which is significant at the 0.01 level. The R_2 Statistic is 0.574 as shown in Figure 2. The data 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 of time between awareness and adoption was observed in respondent 58 who first became aware in 2003 but did not adopt until 2014, a lag of 11 years and adoption was described as a collective decision. Whilst these individual data points could be isolated to argue the slow diffusion of technological and process based innovations in the construction industry, the usual time lag recorded between awareness and adoption was recorded as being between 1.75 – 3.00 years.

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*' and then depending upon the response Q45/46 asked which type of decision was made to adopt/reject 4D BIM Innovation. 65.0% of respondents (n = 52) confirmed that a decision had been made to adopt 4D BIM for the planning of construction work, with 1.3% (n = 1) of respondents conforming that a decision had been made to reject 4D BIM innovation. 33.8% (n = 27) of respondents selected the undecided/no decision made option. Rogers (2003) categorisation of decision types were specified as: '*Optional Decisions*', where a decision was made by the individual; '*Collective Decisions*' made by consensus; and '*Authority Decisions*', made by organisational upper management. A majority of the adopters, 32.5% (n = 26) identified that the decision to adopt had been an 'authority decision', with the collective decision making being the next most frequent option with 18.8% (n = 15) followed by individual 'optional' decision making with 13.8% (n = 11) of the responses.

Relative advantages of 4D BIM against construction planning functions

The functions of construction planning practice were identified from a review of the wider construction planning literature: (A) *work winning;* (B) *design interrogation;* (C) *planning construction methods;* (D) *visualising the construction process;* (E) *facilitating understanding of the construction process;* (F) *validating the time schedule;* (G) *location based planning;* (H) *progress reporting;* (I) *site layout planning (positions);* (J) *logistics planning (movements);* (K) *communicating working space; and* (L) *safety planning*. 5-point Likert scales were used to measure strength of agreement as to where 4D BIM could offer a relative advantage against these factors and the online questionnaire was designed to randomise the response options to avoid response set tendency. Spearman's Rho was used to establish correlation and significance in the strength of the relationships between these variables. Table 2 identifies the many significant associations, whilst the largest correlations are between (J) logistics planning (movements) and (K) the communication of working space (.668) and between (B) interrogating design and (D) visualising the construction process (.576), meaning that 4D BIM is considered to be more effective than traditional construction planning for these purposes.

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 construction planning process which was identified in the literature as: (A) *gathering information;* (B) *identifying activities;* (C) *assessing activity durations;* (D) *planning the logical dependencies;* (E) *planning the construction sequence;* (F) *communicating the construction plan; and* (G) *communicating project timescales*. Table 3 again identifies many significant associations, however the largest correlations are between (D) planning logical dependencies and (E) planning construction sequence (.643), and between (A) gathering information and (E) planning construction sequence (.566) again meaning that 4D BIM is deemed to be more effective than traditional construction planning for these purposes.

Table 2: Functions - strength of relationships: Nonparametric Correlations. Correlation significant at the 0.05 level (2-tailed). Correlation significant at the 0.01 level (2-tailed)**.*

		A	B	C	D	E	F	G	H	I	J	K	L
A	CC	1.000	.347**	.347**	.485**	.279*	.329**	.282*	.297**	.440**	.325**	.316**	.387**
	Sig	.	0.002	0.002	0.000	0.012	0.003	0.011	0.007	0.000	0.003	0.004	0.000
B	CC	.347**	1.000	.438**	.576**	.280*	.323**	.289**	.406**	0.219	0.154	.328**	0.110
	Sig	0.002	.	0.000	0.000	0.012	0.004	0.009	0.000	0.051	0.174	0.003	0.329
C	CC	.347**	.438**	1.000	.467**	.488**	.424**	.366**	.485**	.252*	.322**	.335**	.427**
	Sig	0.002	0.000	.	0.000	0.000	0.000	0.001	0.000	0.024	0.004	0.002	0.000
D	CC	.485**	.576**	.467**	1.000	.451**	.380**	.335**	.422**	.309**	0.217	.345**	0.177
	Sig	0.000	0.000	0.000	.	0.000	0.001	0.002	0.000	0.005	0.053	0.002	0.117
E	CC	.279*	.280*	.488**	.451**	1.000	.280*	.419**	.408**	.295**	.478**	.538**	.253*
	Sig	0.012	0.012	0.000	0.000	.	0.012	0.000	0.000	0.008	0.000	0.000	0.024
F	CC	.329**	.323**	.424**	.380**	.280*	1.000	.369**	.473**	0.006	.266*	.248*	.352**
	Sig	0.003	0.004	0.000	0.001	0.012	.	0.001	0.000	0.957	0.017	0.027	0.001
G	CC	.282*	.289**	.366**	.335**	.419**	.369**	1.000	.280*	.343**	.293**	.426**	.260*
	Sig	0.011	0.009	0.001	0.002	0.000	0.001	.	0.012	0.002	0.008	0.000	0.020
H	CC	.297**	.406**	.485**	.422**	.408**	.473**	.280*	1.000	.232*	.329**	.307**	.468**
	Sig	0.007	0.000	0.000	0.000	0.000	0.000	0.012	.	0.039	0.003	0.006	0.000
I	CC	.440**	0.219	.252*	.309**	.295**	0.006	.343**	.232*	1.000	.516**	.475**	.251*
	Sig	0.000	0.051	0.024	0.005	0.008	0.957	0.002	0.039	.	0.000	0.000	0.025
J	CC	.325**	0.154	.322**	0.217	.478**	.266*	.293**	.329**	.516**	1.000	.668**	.260*
	Sig	0.003	0.174	0.004	0.053	0.000	0.017	0.008	0.003	0.000	.	0.000	0.020
K	CC	.316**	.328**	.335**	.345**	.538**	.248*	.426**	.307**	.475**	.668**	1.000	.346**
	Sig	0.004	0.003	0.002	0.002	0.000	0.027	0.000	0.006	0.000	0.000	.	0.002
L	CC	.387**	0.110	.427**	0.177	.253*	.352**	.260*	.468**	.251*	.260*	.346**	1.000
	Sig	0.000	0.329	0.000	0.117	0.024	0.001	0.020	0.000	0.025	0.020	0.002	.

Table 3: Processes - strength of relationships: Nonparametric Correlations. Correlation significant at the 0.05 level (2-tailed). Correlation significant at the 0.01 level (2-tailed)**.*

		A	B	C	D	E	F	G
A	CC	1.000	.527**	.520**	.434**	.566**	.250*	.488**
	Sig	.	0.000	0.000	0.000	0.000	0.026	0.000
B	CC	.527**	1.000	.387**	.392**	.521**	.344**	.407**
	Sig	0.000	.	0.000	0.000	0.000	0.002	0.000
C	CC	.520**	.387**	1.000	.452**	.468**	.228*	.484**
	Sig	0.000	0.000	.	0.000	0.000	0.042	0.000
D	CC	.434**	.392**	.452**	1.000	.643**	.402**	.500**
	Sig	0.000	0.000	0.000	.	0.000	0.000	0.000
E	CC	.566**	.521**	.468**	.643**	1.000	.414**	.391**
	Sig	0.000	0.000	0.000	0.000	.	0.000	0.000
F	CC	.250*	.344**	.228*	.402**	.414**	1.000	.389**
	Sig	0.026	0.002	0.042	0.000	0.000	.	0.000
G	CC	.488**	.407**	.484**	.500**	.391**	.389**	1.000
	Sig	0.000	0.000	0.000	0.000	0.000	0.000	.

Compatibility, complexity, trialability and observability

Several statements were posed relating to these aspects, 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*' and 57.5% (n = 46) in agreement with this statement with 23.8% of respondents (n = 19) remaining neutral, and the remainder disagreeing. Several measures of complexity as a barrier to 4D BIM adoption were considered and the direction of this trend was usually consistent. Q39 was worded '*4D BIM methods would be difficult to learn*' and 40% (n = 32) disagreed with this statement, with 36.3% (n=29) remained neutral, and the remainder agreeing. Q40 '*4D BIM methods would be difficult for planners to understand*' also found a majority 56.3% (n = 45) disagreeing with this statement, with 26.3% (n=21) remaining neutral, and the remainder agreeing. Q41 '*The training required in order to learn 4D BIM methods would be complicated*' was similar with 45.1% (n = 36) disagreed with this statement, however in this question more respondents 32.5% (n=26) agreed with this statement than the 22.5% (n = 18) that remaining neutral. To measure trialability Q42 stated '*4D BIM methods would have to be experimented with before using to plan real construction work*' and 55% (n = 44) agreed with this statement with 25.0% (n = 20) disagreeing. To measure observability Q43 stated '*It is easy to see the impact that 4D BIM has on construction planning effectiveness*' and 70.0% (n = 56) agreed with this statement with 20.0% (n = 16) remaining neutral and the remainder disagreeing.

Communication channels

Respondents were asked two questions in relation to communication channels. Q47 asked '*Please select your preference for obtaining information about 4D BIM*' and 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*' The same two response options were provided for both questions '*External Sources, i.e.: Mass media including websites, journals, magazines; government*' and '*Internal sources i.e.: Colleagues, peers, workmates or interpersonal networks*'. At the outset of this study a set of hypotheses was formed and able to be 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 80 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 (43.8%) was between external sources for information preference and internal influences for impact upon decision making, which supports 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"*.

CONCLUSIONS

Results indicate a growing rate of 4D BIM innovation adoption for the planning of construction projects with a typical lag of 1.75 - 3 years between awareness and first use. Innovation adoption decisions are then typically authority decisions made by organisational upper management and exploration of the data at individual case level also reveals slow rates of diffusion for those with early awareness of this innovation but without these authority adoption decisions. Many construction planning functions and stages of the construction planning process are considered to be more effective using 4D BIM than current construction planning practices. Whilst compatibility and observability remain important aspects of any innovation adoption, concerns over training complexity and opportunities for trialling the innovation seem more prominent as barriers to 4D BIM adoption. The study also confirms Rogers (2003) assertion that it is *"interpersonal communication with near peers drives the diffusion process"* in that adoption/rejection decisions are more likely to be influenced by internal factors than external factors. With additional data, analysis will be extended to permit further inferential statistical analysis to explore associations between the extent and nature of 4D BIM use for construction planning and the characteristics of user organisations such as size and BIM maturity.

REFERENCES

Barnlund, C (2008) A transactional model of communication. In. C. Mortensen (Eds.), *"Communication theory"*, 2nd ed. New Brunswick, New Jersey: Transaction.

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

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

Constructing Excellence (2014) *"UK Industry Performance Report 2013"*. Based on the UK Construction Industry Key Performance Indicators.

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

Cullen, J and Nankervis, C (1985) Overcoming the luddite factor: some behavioural aspects of the field supervisor's role in construction planning. *" Journal of Project Management"*, **3**(3), 133–140.

Dawood, N (2010) Development of 4D-based performance indicators in construction industry. *"Engineering, Construction and Architectural Management"*, **17**(2), 210–230.

Dodgson, M and Gann, D (2010), *"Innovation"*, Oxford, Oxford University Press.

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

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

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"*, **30**(8), 687–695.

Gorse, C and Emmitt, S (2007) Communication behaviour during management and design team meetings: a comparison of group interaction. *"Construction Management and Economics, **25**(11), 1197–1213.*

Gorse, C and Emmitt, S (2009) Informal interaction in construction progress meetings. "Construction Management and Economics", **27**(10), 983-993.

Hartmann, T and Fischer, M (2007) Supporting the constructability review with 3D/4D models. *"Building Research and Information"*, **35**(1), 70–80.

Hartmann, T, Gao, J and Fischer, M (2008) Areas of Application for 3D and 4D Models. *"Journal of Construction Engineering and Management"*, **134**(10), 776–785.

HM Government (2013) Construction 2025. Industrial Strategy: government and industry in partnership. London.

Koo, B and Fischer, M (2000) Feasibility Study of 4D CAD in Commercial Construction. *"Journal of Construction Engineering and Management"*, 126(4), 251–260.

Li, H, Guo, H, 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"*, **29**(3), 233–245.

Li, H, Huang, T, Kong, C, Guo, H, Baldwin, A, Chan, N and Wong, J (2008). Integrating design and construction through virtual prototyping. *"Automation in Construction"*, **17**(8), 915–922.

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

Mahalingam, A, Kashyap, R and Mahajan, C (2010) An evaluation of the applicability of 4D CAD on construction projects. *"Automation in Construction"*, **19**(2), 148–159.

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

Reza Hosseini, M, 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"*, **15**(2), 151–179.

Rogers, E (2003) *"Diffusion of Innovations"* (5th ed.). New York, N.Y.: Free Press, Simon and Schuster.

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

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"*, **167**(1), 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"*, **49**, 83–91.

Winch, G and Kelsey, J (2005) What do construction project planners do? *"International Journal of Project Management"*, **23**(2), 141–149.