Evaluating Research Methodology in Construction Productivity Studies

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Abstract

Despite the large number of published papers in the area of construction productivity, a critical review of contemporary thinking with a discussion of the implications to current researchers is rarely attempted. As such, this paper investigates the subject based upon published papers in major peer-reviewed journals during the last decade. Eighty-nine papers published in both construction journals and broader management science journals have been analysed. Three broad classifications were used for summarizing the methodologies adopted within the papers: Qualitative, quantitative and mixed-method research approaches. The research taxonomy further identified three major fields based on each study's research focus: Archival studies, empirical research and simulation proposals. In terms of the methodological structure followed, three main categories have been recognised: Experimental frameworks, data collection techniques and modelling proposals. A methodological framework is developed upon the evaluation's results and its implementation on an actual research project is illustrated. The main conclusion is that the selection of the research methodology in published journal papers has been an intuitive decision, mainly relating upon the researcher's ontological and epistemological stance. However, general guidelines on the selection of the most appropriate methodology in relation to the research aims and objectives may also be proposed.

Keywords: Construction, Methodology, Productivity, Research

Introduction

The research methodology encompasses the rationale and the philosophical assumptions that underlie a particular study (Dainty, 2008). The choice of research strategy drastically influences the specification of the research methods that are deployed for investigating a problem and determines the research design, namely the framework for collecting, analysing and interpreting data (ibid.). The establishment of the most appropriate methodology for construction research is a current subject of concern. This is corroborated by the special issue of the *Journal of Construction Engineering and Management* (Volume 1, Issue 1) on research methodologies for Construction which only appeared at the beginning of 2010. A previous somewhat organised approach to the subject can be traced back in the mid to late 1990's with a series of papers appearing in *Construction Management and Economics* (Volumes 13-16). The review of those and some other supplementary sources (from relevant papers which did not appear in the above mentioned journals and periods) has led to a number of questions relating to construction management research methodological issues: What are the most suitable criteria for selecting the research methodology? How can the rigour and robustness of a research effort be evaluated? What are the current trends?

The above and similar questions have formed the motivation for the research described in this paper. More specifically, the objective of this paper is to provide answers to the above questions, with a particular focus on research related to construction productivity (CP). The field of CP is an expedient research area since the complex and versatile nature of the subject has led to the implementation of multiple method approaches. As such, this study explores the different perspectives for measuring or estimating construction productivity. The main purpose is to capitalise on the trend towards methodological rigour and comprehensiveness by soliciting papers on methodologies that are identified as being typically employed in construction productivity research.

The paper's structure is as follows: First, some basic concepts of construction productivity are introduced, followed by a discussion on the research methodology, with a particular focus on the evaluation of the adopted research strategy and the development of the research taxonomy. Then, the analysis of the results is presented and a demonstration of the application of the explored concepts on an actual research project is provided within the framework of a structured approach. Finally, the inferences emerging from the study are discussed and the main conclusions are formulated.

Construction Productivity

In general terms, construction productivity can be simply illustrated by an association between an output and an input, as shown in Equation 1 (Park, 2006).

$$\text{Productivity} = \frac{\text{Output}}{\text{Input}} \text{ (Equation 1)}$$

There is no standard way to define productivity for construction operations. However, the norm is that for equipment-intensive operations, productivity is defined as output / input (i.e. m^3/h for excavation works), whereas for labour-intensive operations productivity is defined as input / output (i.e. $0.50h/m^2$ for wall formwork operations). The same convention is going to be used in this paper as well.

The level of analysis is associated with the scope of the productivity study, namely the extent of the variables taken into account in the estimation process. This paper is focusing on the project- and activity-level analysis, where the role of different types and number of factors affecting the on-site productivity is explored. In these studies the production rates and their variations are studied for specific construction activities and their respective set of tasks (Shi, 1999a), thus imposing several challenges in terms of the methodological approach that is to be followed. More details regarding the evaluation of the research methodology, from a construction management perspective, are provided in the next section.

Research Methodology

Evaluation of the adopted research methodology

The doctoral studies in construction management differ significantly from other disciplines since the latter is not an academic discipline in its own right, with its own research techniques and theories, but rather builds upon theoretical models developed elsewhere in the social sciences (Hughes, 1994). As such, the doctoral researcher must be able to decide upon the research methodology and formulate the adopted research strategy in such a way, so as to be in accordance with the aims and objectives of the study while, at the same time, ensuring an original contribution to an existing body of knowledge (Grix, 2001; p. 12). In addition, irrespective of the adopted approach and the innovative characteristics, every scholarly endeavour must be conducted within a framework which is directed towards the achievement of validity and reliability for the results and conclusions emerging from the study (Lucko and Rojas, 2010).

However, until today there is no unanimous agreement as to what approach is more suitable for conducting academic or doctoral research. The debate on construction research as expressed in Seymour et al. (1997) resulted in a controversy between academics favouring the positivist perspective, which is closely related to rationalism, empiricism and objectivity (Hariss, 1998) and the ones in favour of the interpretivistic approach, which highlights the subjectivity of truth and reality since it depends on the persons investigated (Rooke et al., 1997). Traditionally, the former is associated with quantitative research, whereas the latter is related to the qualitative research approach (Fellows and Liu, 2003). However, the current research trend seems to extend beyond the sterile debate limited by the dichotomies of the past and supports a shift towards encouraging multiple theoretical models and method approaches to be employed in construction management research, often termed as “multi-method” (Dainty, 2008). The latter is particularly relevant for CP research, where social and natural science methods are frequently intertwined (Abowitz and Toole, 2010).

As this study’s objective is to critically review published research on construction productivity irrespective of the adopted approach, a challenge for the authors was the formulation of a concise and generic set of criteria for the evaluation of all types of research efforts included in the analysis. It has been decided to use two metrics:

- The researcher’s *ontological and epistemological stance* (Dainty, 2008); and
- The satisfaction of the *unique adequacy (UA) requirement* of methods, as proposed by Rooke and Kagioglou (2007).

Ontology refers to the conceptions of reality, the claims and assumptions upon which a theory is based (Grix, 2001). Ontological positions are divided in “objectivist ontology” which evaluates social phenomena independent of the social actions (usually associated with the quantitative approach) and “constructivist ontology” which recognises that social phenomena are dynamic and produced through social interaction (usually linked to the qualitative approach) (Dainty, 2008). The researcher’s ontological position is believed to affect the manner in which research is undertaken (Grix, 2001). Epistemology refers to what should be regarded as acceptable knowledge in a discipline and is characterised either by a positivist (quantitative) or interpretivistic (qualitative) perspective as mentioned in the second paragraph of this section (Dainty, 2008). The specification of the ontological stance is a prerequisite for the choice of the epistemological standpoint which, subsequently, leads to shaping the research methodology that is going to be deployed (Grix, 2001). Whereas the first metric evaluates the researcher, the Unique Adequacy (UA) requirement addresses both the researcher and the research itself, through the definition of two satisfaction criteria: the weak and strong forms (Rooke and Kagioglou, 2007). For the UA requirement to be satisfied in its weak form, the researcher must be familiar with the setting under study. For example, a questionnaire should be designed by someone who has direct knowledge of the activity under study. On the other hand, Rooke and Kagioglou (2007) state that the strong requirement concerns the reporting of the research and is based upon the premise that the methods of analysis used to report on a setting should be derived from that setting. In other words, the method of analysis should not necessarily be determined *a priori*, but emerge from the particular setting that is investigated. The UA adequacy is primarily used for evaluating qualitative research without however excluding its application for quantitative approaches. In addition, satisfaction of the weak requirement is a prerequisite for the achievement of the strong requirement (Rooke and Kagioglou, 2007).

Development of research taxonomy

The research strategy used for this paper was to launch a comprehensive review of the CP literature from 1999 to 2009. Eighty-nine (89) papers were selected from top quality journals. 72 papers (81% of the sample) stem from five top quality construction management journals (number of articles in brackets): Automation in Construction (AutoCon) (11), Construction Management and Economics (CME) (10), Engineering, Construction and Architectural Management (ECAM) (5), Journal of Computing in Civil Engineering (JComCE) (5), and Journal of Construction Engineering and Management (JCEM) (41). The rest were found in journals that cover a broader spectrum of management science regarding productivity (e.g. International Journal of Project Management; International Journal of Productivity and Performance Management; Personnel Review).

The qualitative content analysis technique was implemented, so as to introduce some form of taxonomy in the data (Fellows and Liu, 2003). Each paper was analyzed for statements or any other indication of the authors' methodological position and the techniques or methods that were deployed. Where the research methodology, strategy or design was not clearly defined within the paper, the adopted methodology was identified from the narrative description of the research (Dainty, 2008). A three-level hierarchical classification system has been developed for the analysis, as shown in Figure 1.

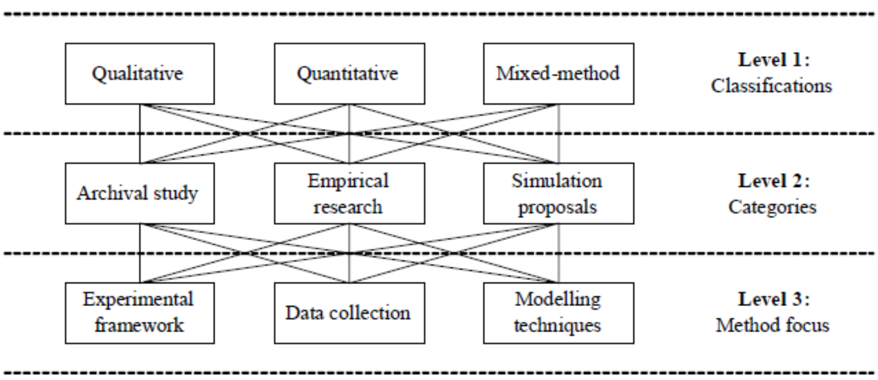

Figure 1: Construction productivity research taxonomy

First, three broad classifications have been used for evaluating the researchers' ontological and epistemological stance: (1) Qualitative research (i.e. interpretative research paradigm), (2) Quantitative research (i.e. positivist research paradigm), and (3) Mixed-method approach (i.e. combination of the first two). A further sub-classification step identified three major categories, based on the research focus of each study: (1) Archival study, (2) Empirical research and (3) Simulation proposals. Archival studies are associated with the analysis of documentary data stemming primarily from secondary rather than primary document sources. Empirical research refers to the creation of models based on observations regarding the responses of a system under investigation for a range of situations (Flood and Issa, 2010). Simulation proposals refer to research studies that induce stochastic modelling and analysis for the representation and interpretation of empirical data. It should be noted that although simulation can be regarded as part of empirical research, it has been decided to be represented by an autonomous category due to its methodological peculiarities (Martinez, 2010). Further analysis on the research methods' focus showed that the utilized tools emphasize mainly on: (1) the development of experimental frameworks, (2) the description of data collection tools and (3) the suggestion of modelling techniques. At this point, it must be clarified that the breakdown of each level in its respective categories is not exclusive and there could be overlaps amongst the research sample. Thus, there has been an attempt to categorise all papers according to their dominant research characteristics. In the next paragraphs, the research taxonomy is elaborated in detail, based on specific data from the sample analysis.

Analysis of Published Research

Descriptive statistics

The total number of papers published in the selected journals in comparison to the CP related papers is shown in Figure 2a below. A more detailed analysis within the selected journals shows that JCEM has the highest publication rate of 3.24% followed by AutoCon by 1.21% (Figure 2b). Papers come from 14 countries, where USA takes the lead with 44 papers, followed by China (including Taiwan and Hong Kong) with 18, as shown in Table 1 illustrating the top-5 countries. Canada, the United Kingdom, Australia and South Korea also seem to be major contributors. Out of 149 researchers, the top-10 most cited authors are shown in Table 2, along with the respective number of publications. In parenthesis is shown the current research institution and published work, in case the author has changed in the last decade. Finally, Table 3 summarises the most frequently cited papers, both within the sample and according to the Institute for Scientific Information's (ISI) index.

In terms of the researched productivity factors, the majority of the papers investigated the effect of change orders, construction methods, personnel management and weather on productivity (4 cases for each factor). The excavator is the most frequently studied piece of equipment (4 cases) and excavation works is the most common field of investigation (13 cases). Concrete operations and steel fabrication works follow with 8 and 7 cases respectively. 19 building projects and 17 earthmoving projects have been investigated, followed by industrial (9), roadworks (5), bridge (1), tunneling (1) and reclamation projects (1).

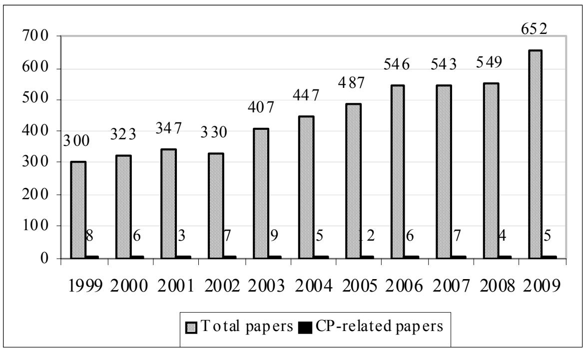

Figure 2a: CP-related papers in selected journals for the period 1999-2009

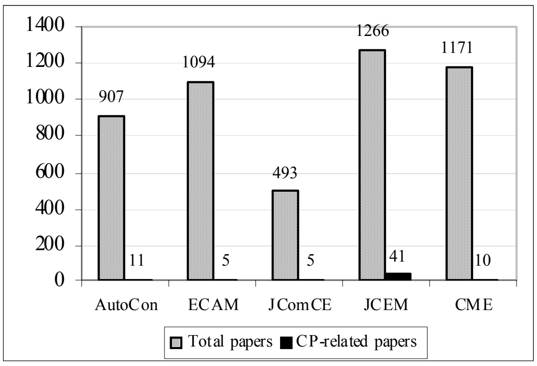

Figure 2b: Published CP-related papers in selected journals

Table 1: Top 5 countries with most published papers

No.	Country	Research centres	Researchers	Papers published
1	USA	20	60	44
2	China	8	24	18
3	Canada	2	16	16
4	United Kingdom	5	13	9
5	Australia	5	6	6

Table 2: Top 10 researchers with most published papers

Researcher	Institution	Country	Papers published	Times cited in sample
Halpin, D.W.	Purdue Univ.	USA	5	109
AbouRizk, S.M.	Univ. of Alberta	Canada	4	94
Thomas, H.R.	Pennsylvania State Univ.	USA	5	90
Martinez, J.C.	Virginia Polytechnic Inst. & State Univ.	USA	1	44
Shi, J.J.	City Univ. of Hong Kong	China	5	38
Moselhi, O.	Concordia Univ.	Canada	3	23
Hanna, A.S.	Univ. of Wisconsin-Madison	USA	6	22
Zayed, T.M.	Purdue Univ.	USA	5	15
Marzouk, M.	Concordia Univ. (Cairo Univ.)	Canada (Cairo)	2 (1)	13
Tam, C., M.	City Univ. of Hong Kong	China	4	9

Table 3: Most frequently cited papers

No	Author/year	Title	Publication	Sample index	ISI index
1	Martinez, J.C. and Ioannou, P.G. (1999)	General-purpose systems for effective construction simulation	JCEM[1], 125(4)	9	48
2	Hajjar, D. and AbouRizk, S.M. (2002)	Unified modeling methodology for construction simulation	JCEM, 128(2)	6	33
3	Shi, J.J. (1999)	Activity-based construction (ABC) modeling and simulation method	JCEM, 125(5)	7	28

4	Hanna, A.S. et al. (1999)	Impact of change orders on labour efficiency for electrical construction	JCEM, 125(4)	4	26
5	Hanna, A.S. et al. (1999)	Impact of change orders on labour efficiency for mechanical construction	JCEM, 125(3)	5	23
6	Thomas, H.R. et al. (1999)	Loss of labour productivity due to delivery methods and weather	JCEM, 125(1)	6	20
7	Cheng, T.M. and Feng, C.W. (2003)	An effective simulation mechanism for construction operations	AutoCon[2], 12(3)	1	19
8	Thomas, H.R. and Zavrski, I. (1999)	Construction baseline productivity: theory and practice	JCEM, 125(5)	3	17
9	Zayed, T.M. and Halpin, D.W. (2001)	Simulation of concrete batch plant production	JCEM, 127(2)	4	17
10	Thomas, H.R. (2000)	Schedule acceleration, workflow and labour productivity	JCEM, 126(4)	2	17

[1] Journal of Construction Engineering and Management (ISI Impact Factor 0.564)

[2] Automation in Construction (ISI Impact Factor 1.664)

Evaluation of research methodology

The adopted research methodology is a reflection of the researcher's ontological and epistemological stance. In the field of CP, the application of quantitative research dominates (60.7%), followed by the mixed-method (29.2%) and the qualitative approaches (10.1%) (refer to Table 4). A more detailed analysis on each one of those approaches, based on their ontological and epistemological standpoint, follows in the next paragraphs.

Table 4: Research classifications and categories

	Level 2: Categories			
Level 1: Classifications	**Archival study**	**Empirical research**	**Simulation proposals**	**Total**
Quantitative	5 (5.6%)	26 (29.2%)	23 (25.9%)	54 (60.7%)
Qualitative	5 (5.6%)	4 (4.5%)	0 (0.0%)	9 (10.1%)
Mixed-method	8 (9.0%)	16 (18.0%)	2 (2.2%)	26 (29.2%)
Total	**18 (20.2%)**	**46 (51.7%)**	**25 (28.1%)**	**89 (100%)**

Quantitative research approach

The quantitative approach is primarily associated with empirical research (29.2%), followed by the formulation of simulation proposals (25.9%) and the performance of archival studies (5.6%). The empirical research approach has been implemented for the development of mathematical models that represent abstractions of construction systems aiming at delineating the effect of a pre-selected set of variables or factors on productivity. As such, it is fair to suggest that the majority of the papers is linked to objectivistic research philosophies, from the ontological point of view. Similarly, the studies' epistemological standpoint lies closer to the positivist paradigm. For example, in one of the most frequently cited studies, Thomas et al. (1999) studies the impact of weather and material delivery methods on labour-intensive productivity for three steel erection projects by proposing a generic analytical framework that could be applied independently of the project actors. In a similar effort, an equipment-oriented productivity estimation framework was reported by Schabowicz and Hola (2007) depending solely on operational parameters such as fleet size, machine capacity and type of road surface. The same methodological principles were implemented in the work of Ng et al. (2004) who specified predominant demotivators influencing productivity of construction projects in Hong Kong by objectively quantifying the negative effects in terms of the lost man-hours. Notice that all of the above reviewed studies adhered to the application of natural science methodologies such as multiple regression techniques (Thomas et al., 1999), artificial neural networks (ANN) (Schabowicz and Hola, 2007) and quantitative surveys (Ng et al., 2004).

Quantitative simulation research is founded upon mathematics, probability and statistics. From an ontological point of view, simulation studies attempt to derive a semantic content from models which represent actual systems (Martinez and Ioannou, 1999). Simulation models are divided in the implementation of General Purpose Simulation (GPS) platforms, such as CYCLONE, MicroCYCLONE, STROBOSCOPE or EZStrobe (Marzouk and Mosehli, 2003; Zhang et al., 2007), and the utilization of Special Purpose Simulation (SPS) tools, such as SIMPHONY (Mohamed and AbouRizk, 2005). General purpose simulation tools are not domain-specific and can be used to model practically any operational scenario (Martinez and Ioannou, 1999), whereas special purpose simulators enable practitioners knowledgeable in a specific construction domain to model a project without necessarily being an expert in simulation itself (Hajjar and AbouRizk, 2002). Objectivism dominates in simulation research, since in both GPS and SPS studies the developed models reflect an abstraction of the actual system, isolated from its general context. Moreover, the application of quantitative modeling methods such as probabilistic analysis (Huang and Hsieh, 2005) and stochastic data modeling (Rustom and Yahia, 2007) demonstrate simulation's relationship to the positivist epistemological stance.

Archival studies implementing the quantitative research methodology regard the retrospective study of historical data, so as to determine the critical factors that affect the on-site productivity threshold. Once again, this category verifies the construction management community's predilection towards the establishment of an objective conception of reality through the application of natural sciences methods. Such an approach has been adopted by Graham and Smith (2004) who gathered past productivity data regarding the concrete supply and on-site delivery and created a predictive model by applying Case Based Reasoning (CBR) principles. In the same way, Song and AbouRizk (2005) utilised historical data to quantitatively predict productivity through the development of an empirical framework (Quantitative Engineering Project Scope Definition – QEPSD) associating steel drafting building elements' type (e.g. columns, beams) and complexity (e.g. number of fittings) with the resulted work hours.

Qualitative research approach

The qualitative research methodology is implemented for archival analysis (5.6%) or empirical work (4.5%) within the framework of exploratory surveys. The archival studies utilise past data and expert experience to develop conceptual frameworks for measuring productivity (Crawford and Vogl, 2006), to specify the factors that might influence on-site performance (Park, 2006) or to formulate general principles that govern construction productivity (Thomas and Horman, 2006). On the other hand, qualitative empirical research is almost exclusively linked with questionnaire surveys in an attempt to explore the role and significance of specific factors which are believed to affect productivity. It should be noted that there seems to be no clear distinction regarding the adopted ontological and epistemological standpoint. However, without entirely abandoning the deductive research approach there is a tendency to depart from the norm towards the adoption of a more constructivistic and interpretivistic stance for interpreting the behavioural patters adopted by construction operatives. For example, Rojas and Aramvareekul (2003) studied labour productivity drivers and productivity within the US construction industry by surveying a variety of project actors (e.g. owner, consultant, contractor etc.) and concluded that personnel management skills and manpower issues are the two main improvement drivers, thus bringing "people" at the forefront of attention. The latter has been verified by Dai et al. (2009) who took a "bottom-up" approach by examining the craft workers' perceptions in the US regarding the relative impact of 83 productivity factors (e.g. behavioural issues, safety, project management, communication skills) through a series of focus groups sessions. In a similar fashion, Chan and Kaka (2007) investigated construction productivity factors in the UK through a questionnaire survey targeted at both white-collar managers and blue-collar workers combined with in-depth interviews.

Mixed-method research approach

The mixed-method approach in CP research is associated with the deployment of qualitative and quantitative techniques for data elicitation and analysis respectively. Therefore papers with a mixed-method design combine empirical work or archival study with quantitative modelling of productivity data for the formulation of mathematical models or simulation tools. In archival research, the mixed-method approach incorporates unobtrusive research methods (e.g. document analysis, use of existing organizational or company data) combined with statistical regression or artificial neural networks modelling methodologies. For example, Thomas and Zarvski (1999) studied numerical project databases consisting of labour productivity measurements for masonry, concrete formwork and structural steel activities from 42 construction projects and conducted statistical analysis to calculate specific productivity metrics to identify the best and worst performing projects. A historical database of productivity data was also studied by Song and AbouRizk (2008) to extract datasets which were subsequently used to train ANN and develop productivity models for steel drafting projects.

The applications of mixed-method research in empirical studies are not substantially diversified from the principles of methodological pluralism, since the majority of the papers adheres to the approach presented in the previous paragraph. The main differences are found in the data elicitation techniques, where questionnaire surveys are primarily used instead of meta-data or document analysis. Cottrel (2006) associated qualitative and quantitative variables, such as project management vision, dedication and experience (called Process Improvement Initiatives – PII) with job site productivity via the use of multiple regression analysis. Furthermore, Ok and Sinha (2006) studied dozer operations and developed both a statistical regression model as well as an artificial neural network model to associate operational (e.g. blade type) and behavioural (e.g. site management's efficiency) factors with productivity estimation. A similar approach has been followed for the implementation of the mixed-method research approach in developing simulation models based on data gathered from on-site field observations (Al-Sudairi, 2007) or time studies (Anson et al., 2002).

Evaluation of research methods and tools

Taking a more detailed view, Table 5 shows that archival and empirical CP research is essentially equally focused on developing experimental frameworks, improving data collection tools and delineating modelling techniques, whereas the latter is almost the exclusive objective of simulation studies (in 19 out of 25 cases). The results of the analysis for the respective methods' focus are discussed in the following paragraphs.

Table 5: Research categories and method focus

	Level 3: Method focus			
Level 2: Categories	**Experimental framework**	**Data collection**	**Modelling techniques**	**Total**
Archival study	7 (7.9%)	5 (5.6%)	6 (6.7%)	18 (20.2%)
Empirical research	16 (18.0%)	14 (15.7%)	16 (18.0%)	46 (51.7%)
Simulation proposals	4 (4.5%)	2 (2.2%)	19 (21.3%)	25 (28.1%)
Total	**27 (30.3%)**	**21 (23.6%)**	**41 (46.1%)**	**89 (100%)**

Archival study

In archival studies the development of experimental frameworks is mainly targeted at testing new models, validating existing concepts and conducting comparative analyses. The methods used vary depending on the purpose and type of research; however in their majority they are linked to statistical analysis. For example, Hanna et al. (2002) were based on an existing linear model to study the effect of the quantitative and qualitative input variables on enhancing or reducing the impact of change orders on labour productivity expressed in percent loss of labour productivity. They used an integrated method based on regression analysis combined with fuzzy logic. Mohamed and Srinavin (2005) developed a similar methodology which was based solely on statistical regression analysis methods, so as to formulate and test an experimental productivity model which would encapsulate the effect of thermal comfort, representing the influence of the external environment, on productivity of labour-intensive operations. The model's validity was tested through a series of comparative analyses with similar, previously published models. In the same fashion, Thomas (2009) implemented statistical analysis methods to conduct cause-effect analysis on historical cumulative productivity measurements, so as to evaluate the significance of the learning curve effects on construction operations.

Data collection techniques in archival studies are primarily associated with methods that aimed at eliciting data for verifying hypotheses formulated on the basis of a literature review. Doloi (2008) used a structured questionnaire to investigate the effect of planning, incentives and job satisfaction on productivity. An extensive literature review helped in specifying 72 questions which were included in the questionnaire and the Analytical Hierarchy Process (AHP) method was used to analyze the results so as to prioritise solutions for improving productivity in construction projects. In a similar approach, Zhai et al. (2009) studied an existing database of productivity measurements provided by the Construction Industry Institute (CII) in the USA and used an automation and integration index to determine the extent to which construction information systems had been utilised in construction projects. Statistical analysis was subsequently implemented to associate the automation level with productivity. Closely related to the above study is the work of Goodrum et al. (2009) who reviewed a series of price books to extrapolate productivity data and associated it with the state of construction material technology for specific sets of construction activities. Once again, statistical analysis was deployed to find a quantifiable positive relationship between improvements in material technology and respective improvements in construction productivity.

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The preferred modelling techniques in archival studies are the development of linear models, the training of artificial neural networks, either as a stand-alone technique or combined with other tools and the application of knowledge-based systems. The deterministic, linear modelling technique has been applied by Zayed and Halpin (2005a) for the development of a cycle time estimation model of pile construction operations. Tam et al. (2002) used artificial neural networks to model the digging depth, swing angle and bucket capacity of hydraulic excavators and associated it to their on-site productivity. Excavation operations were also studied by Chao (2001) who extended the previous approach by combining ANN with simulation to estimate the cycle time and work zone width of excavators. Furthermore, Mosehli et al. (2005) utilized the ANN technique for modelling labour-intensive operations based on historical company-specific data of construction projects. Finally, taking a different modelling stance, El-Rayes and Mosehli (2001) created a database of climatic historical data and combined it with knowledge-based rules to create an expert system (WEATHER) which could estimate the lost productivity due to rainfall on highway construction. The model was validated with actual data from contractors and public agencies.

Empirical research

The development of experimental frameworks in empirical CP research comprises a variety of methods, such as field experiments or laboratory tests, controlled experiments, comparative evaluations and generic productivity measurement models. Smith et al. (2000) specified a new methodology for estimating truck cycle times in earthmoving operations where the rolling resistance of haul roads made up of cohesive soil was calculated based on the soil's geotechnical properties (moisture content, plastic limits), as defined by field experiments, instead of using empirical, indicative values. In addition, Mrad et al. (2002) simulated the kinematics of an excavator to analyse its trajectory and used an educational robot to experiment and confirm the predicted results. Furthermore, Maciejewski et al. (2004) executed an experimental program of laboratory tests to explore the influence of the excavator bucket teeth on the efficiency of the digging cycle by measuring the developed resistance forces and soil displacements. In another equipment-oriented study, Lee et al. (2003) aimed at improving health and safety during pipe laying operations and, thus, developed a tele-operated pipe manipulator which was subsequently evaluated during field tests using both qualitative and quantitative performance criteria. In a similar effort, Bernold (2007) established a full-scale backhoe simulator facility equipped with electronic sensors and through a series of experiments quantified the performance of backhoe operators who executed standard excavation scenarios (e.g. trenching under a pipe). Apart from lab or on-field experiments, empirical research comprises the performance of controlled, comparative experiments, such as the work of Grau et al. (2009), who evaluated the impact of automated material tracking technologies on decreasing the time needed for material processing and hence improving on-site productivity in contrast to traditional material management practices. In addition, Zhao et al. (2009) built a chamber stimulating hot and humid environment and utilised statistical analysis to evaluate the significance of the thermal environment on labour productivity. Another application of comparative methods comes from Enshassi et al. (2007) who benchmarked masonry labour productivity based on a generic statistical methodology which compared actual project data to accepted industry standards. The experimental frameworks for CP empirical research are usually based on the formulation of a generic measurement model which is subsequently applied for the investigation of different productivity influencing factors. A characteristic example is the work of Hanna et al. (2005) who defined a statistical productivity measurement framework based on the comparison of the budgeted work hours to the actual work hours expended to reach completion. The framework was used to investigate the impact of extended overtime on productivity. The same concepts, although somewhat altered, have been subsequently used for the evaluation of other factors such as overmanning (Hanna et al., 2007) and shift work (Hanna et al., 2008) on labour productivity. Apart from statistical models, simulation frameworks have been also formulated, such as the work of Zayed and Halpin (2004), who defined a productivity measurement framework of pile construction operations or the model of Huang et al. (2004) who used computer process simulation techniques to estimate the productivity of gang formwork operations.

The most commonly used data collection techniques for empirical CP research fall within a spectrum between two categories: continuous observation (e.g. time studies, time-lapse visual techniques, image analysis) and intermittent observation methods (e.g. passive observation, application of structured data elicitation protocols, deployment of specialized data elicitation instruments). The work of Dunlop and Smith (2004) belongs to the first category since they observed more than 200 concrete pours on three separate civil engineering projects and performed time studies to register relevant data, such as number and size of pours, truck mixer volume, trucks fleet size and mean cycle time. The objectivity of the observer and the consistency of measurements are key prerequisites to ensure validity of measurements while conducting time-studies. Tam et al. (2004) obtained hook times of mobile cranes with the help of the time-lapse video-recording technique which were used as inputs to train artificial neural networks. Image analysis was applied by Zou and Kim (2007) so as to automate the identification of idle times for hydraulic excavators and hence improve productivity on site. Passive observation is implemented when the researcher does not actively participate in the data collection process (e.g. declare to site personnel that a time study is being conducted), but rather stays a passive observer of what is happening on site (Bernold and Lee, 2010). This approach has been implemented by Lee et al. (2007) in an attempt to monitor and compare the production rates of freeway rehabilitation projects in California. A similar technique was applied by Dunston et al. (2000) while observing asphalt overlay operations on urban highways. Due to the importance of data validity, some authors have developed a structured framework for collecting productivity data. Proverbs et al. (1999) administered a structured questionnaire amongst construction operatives in the UK, Germany and France to collect and compare productivity rates for high rise concrete construction. In a similar fashion, AbouRizk et al. (2001) created a standardized report which enabled the collection of productivity information (e.g. project costs, design details, activity characterization, indicative rates) for pipe installation activities. Personal and phone interviews were used to gather additional data. Park et al. (2005) took a more systematic approach and developed a Construction Productivity Metrics System (CPMS) which was used as a standard collection tool and a framework to report industry norms and benchmark construction productivity. In addition, O'Connor and Huh (2006) developed a process-oriented data collection tool which described in detailed steps the actions of the researcher, in order to collect valid productivity data starting from the definition of the candidate projects, going over the site visit and concluding with the organisation of the collected data. In some cases, specialized data elicitation tools have been developed to accommodate the special-purpose investigations. For example, Kannan and Vorster (2000) presented a way to automate the collection of truck cycle times by deploying onboard instrumentation and using a set of protocol rules to transform mechanical information (e.g. suspension pressure, transmission position) into usable productivity data (e.g. if suspension pressure is increasing and transmission position is neutral then the truck is being loaded and the time is measured). Truck equipment operations were also studied by Coutermarsch (2007) who explored the effect of vehicle rolling resistance in sand by measuring the rut depth created by the vehicle's wheels. The measurement procedure initiated with levelling the sand prior to each run test followed by the insertion of a thick metal sheet with paper taped to it. At that point, paint was sprayed on the paper showing the upper rut surface. Finally, it should be noted that in some empirical research efforts, where simulation modelling is deployed amongst other techniques, the data collection process includes not only productivity rates but additional types of data, such as arrival/departure times of equipment (Tang et al., 2005) and wait/inactive times of activities (Graham et al., 2005) which are useful inputs for simulation models, as will be shown in the next section.

In terms of the modelling methods deployed in empirical research, the most frequent applications are statistical regression, linear and non-linear mathematical models and probabilistic modelling techniques primarily used for processing the collected data. In addition, fuzzy set theory and artificial neural networks are also deployed. Hanna (1999a; 1999b) studied the effect of change orders on labour efficiency and used two methods: Hypothesis testing and regression analysis. Hypothesis testing was used to compare projects that were impacted (or not impacted) by change, whereas the regression analysis was performed to establish a model that would quantify the effect of change as well as estimate the impact on labour efficiency on future projects. Edwards and Holt (2000) observed hydraulic excavators' cycle times and used the multiple regression technique to predict future cycle times when the swing angle, the machine weight and the digging depth are known. Similarly, Zayed and Halpin (2005c) used regression techniques to associate cycle time, productivity and cost for pile construction by taking into account operational parameters such as depth and auger height. Hegab and Smith (2007) used a slightly different technique, the regression with life data method, which is specifically suited for assessing failure times. The authors implemented this particular method to analyze the delay time observed in micro-tunnelling projects. Couto and Teixeira (2005) used logarithmic mathematical modelling to develop linear relationships which illustrated the effect of learning curves on high rise floor construction in Portugal. On the other hand, Thomas (2000) studied the effect of schedule acceleration on labour efficiency and developed non-linear regression models which interpreted the labour inefficiencies caused by disrupted work flows. Furthermore, some empirical studies combine quantitative analysis with probabilistic modelling as an additional modelling method, so as to be able to benchmark productivity data. Such an approach is implemented by Zayed and Halpin (2001), who applied simulation modelling to analyze pile construction operations in addition to other modelling techniques (statistical regression, artificial neural networks). The results showed that simulation provided smaller deviations from real case measurements. Fuzzy set theory applications are not that common, but a characteristic one is the work of Yang et al. (2003) who developed a computational intelligent "fuzzy" model with the ability to forecast excavator cycle time based on four predictor variables (machine weight, digging depth, swing angle and ground conditions). Lastly, ANN methods have been used for analysing both equipment- and labour-intensive operations. Shi (1999b) analyzed a load-haul system and developed a neural network model taking as inputs equipment cycle times and weather conditions and providing as outputs productive rates and truck-loader utilisation rates. Zayed and Halpin (2005b) utilized the artificial neural network technique to analyse pile productivity in addition to the analysis mentioned before. Another example of neural networks application for the investigation of labour-intensive operations comes from Ezeldin and Sharara (2006) who developed ANN models to predict productivity of formwork assembly, steel fixing and concrete pouring/finishing operations.

Simulation proposals

The experimental framework of CP simulation research is almost exclusively associated with discrete-event simulation (DES) (Martinez, 2010). A very characteristic implementation of DES methodology is presented by Hassan and Gruber (2008) who developed a simulation framework targeted at the analysis of concrete paving operations. DES provides researchers with a large amount of modelling flexibility since it can be combined with other techniques and methods to enhance modelling capabilities. For example, Zhang (2008) used object-oriented simulation to model earthmoving operations combined with the utilisation of multiple attribute utility (MAU) theory concepts to optimise the results.

In simulation modelling the data collection techniques are similar to those used for empirical or archival studies. For example, Al-Sudairi (2007) used on-field observations (i.e. time studies and video recording) coupled with in-depth interviews with construction operatives to collect data representing the implementation of lean principles on construction projects. In a similar fashion, Rustom and Yahia (2007) conducted time studies where standardised time data sheets were completed by field personnel and the data was fed into a simulation model of an embankment construction project in Gaza beach. On any case, the peculiarities of simulation dictate that the input data should be meticulously tested, so as to ensure that they actually satisfy the basic probabilistic assumptions (i.e. independent and identical distribution of data) required to fit stochastic distributions (Maio et al., 2000).

The modelling techniques depend on the type of the simulation model, with the majority being directed towards the application of General Purpose Simulation techniques. For example, Zhang et al. (2002) induced object-orientation capabilities to the model of Shi (1999a), while Hong et al. (2002) used the ABC modelling technique (Shi, 1999a) to develop a platform that enhanced the visualization capabilities of the existing model. Another example of modifications on the work of Shi (1999a) is the simulation model of Zhang et al. (2003), where fuzzy logic has been added to the simulation of construction operations. Nassar et al. (2003) based their general-purpose simulation model on the STROBOSCOPE language and investigated the productivity of asphalt paving operations under lane closure conditions. Kim and Gibson (2003) developed their own GPS platform for heavy construction operations (*K*nowledge-embedded *MO*dularized *S*imulation system – KMOS) which did not only include object-orientation but also knowledge-based rules for a more efficient representation of the simulated system. Moreover, Lu (2003) proposed a simplified DES approach (SDESA) for construction simulation which resembles the application of the Critical Path Method (CPM), thus being more understandable by engineers. Cheng and Feng (2003) extended the CYCLONE GPS platform so as to include an optimization module based on Genetic Algorithms (GA), in order to find the optimal resource combination for construction operations. Zhang et al. (2005) were also based on the CYCLONE modelling elements to develop a GPS platform incorporating activity object-orientation, which is supposed to offer more control over the performance of simulation experiments.

Special Purpose Simulation tools have been used by many researchers for investigating specific construction operations. For example, Hajjar and AbouRizk (2002) based their approach on the SIMPHONY simulation environment and developed a new method for creating SPS platforms. Indicative applications in earthmoving and aggregates crushing validated their approach. Taking advantage of the CYCLONE and STROBOSCOPE simulation capabilities, Marzouk and Mosehli (2004) developed the SimEarth special purpose simulation program which modelled earthmoving operations and optimized their efficiency by applying GA techniques. Lu et al. (2003) enhanced the SDESA simulation platform with ANN capabilities to form a SPS platform (HCONSIM) for the exploration of a ready-mixed concrete production system in Hong Kong. In addition, Al-Hussein et al. (2006) used the SIMPHONY template and developed a SPS platform for 3D visualisation and simulation for tower crane operations on construction sites. Finally, Said et al. (2009) utilised the STROBOSCOPE simulation engine and analysed bridge deck construction operations in Egypt via a special purpose simulation tool.

Assessment of the UA requirement

Regarding the satisfaction of the UA requirement's weak form, it should be noted that all papers have been compiled by authors that are experienced and possess the required "know how" to conduct CP research. As such, a useful indication would be whether the findings have been used amongst construction practitioners. Looking back at Table 3, it is fair to suggest that the papers with the most citations amongst their colleagues are obviously deemed more useful. On the other hand, the evaluation of the strong criterion satisfaction is difficult to be definitive especially when only 35% of the papers have included a separate research methodology section in the manuscript. For those papers, the danger of failing the strong criterion seems to be two-fold: firstly, in qualitative surveys some authors tend to generalise on the effect of specific factors on productivity by fitting the practitioners' responses to their own perceptions or those of previous research. Secondly, in quantitative research some authors do not provide sufficient data about the limitations in the productivity prediction capabilities of the developed models, which can be particularly detrimental to the research validity especially in the case of statistical regression models.

Development and Application of a Methodological Framework for CP Research

The practical implications of the review's findings will be demonstrated through the analysis of a methodological framework that has been developed by the authors specifically for CP research (Figure 3). The framework enables the empirical evaluation of the effect of selected factors on productivity, while facilitating the comparative analysis of the results. The ultimate objective should be the preservation of the research validity and the establishment of a seamless methodology that could be repeatedly applied for the exploration of differing productivity factors. Notice that the depicted methodological framework is not exclusively linked to doctoral studies, as it is a generic, phase-oriented approach which can be tailored to the needs of the research. A concise presentation of the proposed framework is given below.

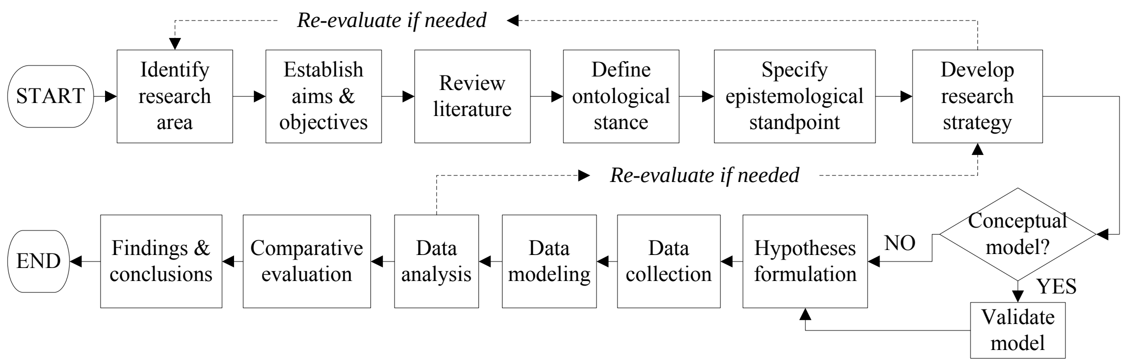

Figure 3: Proposed research approach for construction productivity doctoral research

The first step regards the exploration of the selected research area, so as to identify possible margin for improvement. If the researcher judges that a specific research topic or aspect has not been tackled before and that there is a strong possibility that an original contribution to knowledge can result from the study, then the specific research problem is defined. For example, a research statement, namely a single statement that accurately describes the topic of the research could be formulated. However, no research can be adequately defined without a clear structuring of its respective aims and objectives. The aim encapsulates the essence of the research, whereas the objectives describe the main steps that are going to be implemented for the satisfaction of the research aim. Having done that, the next stage should be the literature review, namely the surveying of information and views already in existence, while maintaining a critical perspective. Subsequently, the researcher should decide on the ontological stance and the epistemological standpoint along the logic presented in the previous sections. Then, the researcher determines the research strategy, namely decides on how a particular piece of research will be undertaken and what methods are going to be used. Research methods diversify in their types and characteristics. The choice of methods will be influenced by the ontological and epistemological assumptions, the research questions that are posed and the type of projects undertaken. It is true that the ontological and epistemological stance of a researcher has a strong influence in developing the research methodology and the very same research question, if approached from a different ontological and epistemological standpoint, can result in different types of findings. However, *"methods themselves should be seen as free from ontological and epistemological assumptions, and the choice of which to use should be guided by the research questions"* (Grix, 2001). In other words, given that the academic community can sometimes be prejudiced against certain methods, while overvaluing some others, it is important that the focus is always on the researcher who employs a particular method in a particular way, thereby associating it with a specific set of ontological assumptions and not on the method *per se*. Moving on to the next step, in case a conceptual model is built, then it has to be validated, and subsequently some basic hypotheses can be formulated regarding the specific research topic. The data collection process is fundamental for ensuring the research validity. A standardised process for eliciting on-field data is needed in order to register all necessary information. The type of data modelling and analysis for the collected data must stem from the sample's characteristics and should not be determined a priori. Data-driven mathematical models, statistical analysis and simulation modelling are possible options. A re-evaluation loop denotes that in some cases the analysis (e.g. from a pilot study) may lead to a differentiation of the research strategy or even a fundamental reconsideration of the research altogether. Comparative evaluation of the results and sensitivity analysis are needed to gain an in-depth perspective of the study's inferences and implications. Finally, the reporting of the findings and the conclusions should reflect the results of the study and be in accordance with the research aims and objectives. No new information should be provided and deductive thinking is usually applied for reporting the inferences emerging from the study. Generalisations should not be made beyond the research scope so as to ensure validity in the results. The next paragraph describes how these concepts can be applied in practice when conducting CP research.

The methodological framework has been implemented in an ongoing research project relating to the association of Health and Safety (H&S) concepts with construction productivity (Panas et al., 2010). A preliminary review of pertinent research indicated that safety practices of construction labour crews had not been included in productivity analyses in a quantifiable and directly measurable manner. As such, a research investigation was launched with the aim of developing comparable productivity models for evaluating the effect of H&S on on-site performance. In view of this aim, the following three objectives were formulated: (i) quantification of the H&S status for a specific construction operation through risk quantification processes, (ii) delineation of the experimental setting for conducting valid productivity measurements in relation to parameters associated with H&S and (iii) setting out the criteria which would allow the comparative analysis of the produced estimates. Analysis of pertinent research along the research taxonomy presented in the previous sections contributed in the critical evaluation of the publications' content, so as to gain a perspective on the body of knowledge specifically linked to the topic. It also aided in deciding upon the ontological and epistemological stance, leading to the adoption of the objectivist and positivist approaches respectively. A conceptual model was developed and a preliminary validation indicated that H&S should be seen from a sustainable perspective, where focus was placed on the adopted construction techniques and behavioural patterns by construction crews. Interviews with construction experts indicated the sources of safety hazard on site and risk quantification tools (e.g. job hazard analysis) were utilised to evaluate the safety level of specific construction processes (e.g. wall formwork operations). A standardised process for eliciting on-field data was developed in order to register all necessary information. Process mapping and simulation-based analysis was used for the creation of productivity models. Statistical regression techniques and sensitivity analysis on selected productivity parameters (e.g. temperature, task difficulty) were utilized to analyse productivity variations compared to baseline estimates. The application of the mixed-method approach by analysing qualitative data from selected interviews combined with quantitative data modelling and analysis provided an insight into the magnitude of variations on performance. The explicit definition of the experimental framework allowed the specification of the study's applicability and respective scope limitations. The latter contributes to overcoming the methodological inconsistency inherent in many productivity studies, which leads to the creation of fragmented models to the detriment of comparative validity.

Discussion and Conclusion

This research had to overcome a number of limitations regarding the sample (e.g. it may not be conclusively representative of the CP related research), the documentation of the research methodologies within the papers (e.g. lack of information, provision of superficial data) and the validity of drawing conclusions based on a given number of sources (e.g. conference proceedings or any type of reports were excluded from the analysis). However, several issues have emerged from the analysis. Firstly, from an ontological and epistemological standpoint, CP research is dominated by the objectivist and positivist stance. That is to be attributed to the strong relation of productivity research to the natural science and the traditional interest in investigating purely technical issues, such as project time and cost. However, the multi-method approach seems to be gaining ground, especially given the industry's shift towards intensifying the exploration of productivity's soft aspects as well, such as behavioural and managerial factors and cultural diversions of the project actors. Secondly, the implementation of methodological pluralism, as found in both empirical and simulation-based productivity research, enhances the chance for minimizing the gap between the "decided" methodology on behalf of the researcher and the "accepted" method by the research community. That is to be achieved by following some basic guidelines, such as (i) explicitly explaining the research methodology to be followed, (ii) objectively reporting the research results, (iii) unambiguously indicating the research's adequacy and (iv) by practically demonstrating how the selected methodology will serve the objectives in order for the research to provide a clear contribution to the existing body of knowledge. In that view, the developed methodological framework and its respective implementation on an actual research study give a perspective of how those guidelines can be practically implemented for CP research. More specifically, in qualitative approaches it is critical to establish the theoretical framework prior to presenting the research results, as productivity factors can be considered multidimensional and can have a different impact or meaning depending on the subjects being investigated. In theoretically driven quantitative empirical work, the clarification of the experimental framework (e.g. type of project and collected data, choice of modelling technique) is vital to understanding the research limitations and thus protecting practitioners from implementing productivity estimation models that do not suit the project's situation. Finally, in mixed-method research approaches, the forms or questionnaires used for the collection of productivity data should be fully explained and excerpts should be provided. In addition, data modelling should be clear on whether it is related to daily or hourly productivity data or even cumulative productivity metrics. At this point, it should be clarified that the framework's structure, as well as its content are based on the inferences emerging from the investigated sample. As such, it reflects the generic characteristics of the research strategies adopted in the scrutinised papers. Hence, its scope should not be generalised beyond that particular context as it could possibly limit the validity of the selected research approach. In that manner, the framework could be criticised for its somewhat prescriptive nature since, for instance, the application of the grounded theory methodology, which does not comprise literature study at the beginning of the research and does not rely on hypothesis testing seems to be excluded from the available options. However, this fact should not be treated solely as a limitation of the proposed approach, but rather (a) as another indication of the researchers' reluctance to adopt less positivist approaches within the CP research field as shown from the sample analysis and (b) as a possible starting point for improvement. In other words, the proposed framework is not an exclusive path to conduct research, but rather a yardstick against which the researchers should critically position themselves according to their ontological and epistemological perceptions by making any respective adjustments or changes that might be necessary to suit the particular research objectives.

This paper has explored the role of research methodologies on construction productivity studies. The main conclusion is that linking different methodological aspects within an integrated research design will contribute towards overcoming both the expected and subtle difficulties of conducting valid research. The adherence to the formulated guidelines is expected to assist current and future researchers in the area of construction productivity to generate research results of greater acceptance by both academics and industrialists.

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