Potential identification and industrial evaluation of an integrated design automation workflow

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Abstract

Purpose – The paper aims to raise awareness in the industry of design automation tools, especially in early design phases, by demonstrating along a case study the seamless integration of a prototypically implemented optimization, supporting design space exploration in the early design phase and an in operational use product configurator, supporting the drafting and detailing of the solution predominantly in the later design phase.

Design/methodology/approach – Based on the comparison of modeled as-is and to-be processes of ascent assembly designs with and without design automation tools, an automation roadmap is developed. Using qualitative and quantitative assessments, the potentials and benefits, as well as acceptance and usage aspects, are evaluated.

Findings – Engineers tend to consider design automation for routine tasks. Yet, prototypical implementations support the communication and identification of the potential for the early stages of the design process to explore solution spaces. In this context, choosing from and interactively working with automatically generated alternative solutions emerged as a particular focus. Translators, enabling automatic downstream propagation of changes and thus ensuring consistency as to change management were also evaluated to be of major value.

Research limitations/implications – A systematic validation of design automation in design practice is presented. For generalization, more case studies are needed. Further, the derivation of appropriate metrics needs to be investigated to normalize validation of design automation in future research.

Practical implications – Integration of design automation in early design phases has great potential for reducing costs in the market launch. Prototypical implementations are an important ingredient for potential evaluation of actual usage and acceptance before implementing a live system.

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The work was carried out within the K-Project # 843551 “Advanced Engineering Design Automation (AEDA),” funded by the Austrian Research Promotion Agency FFG.
Originality/value – There is a lack of systematic validation of design automation tools supporting early design phases. In this context, this work contributes a systematically validated industrial case study. Early design-phases-support technology transfer is important because of high leverage potential.

Keywords Optimization, Design automation, Industrial validation, Potential identification, Product configuration, Seamless integration

Paper type Case study

1. Introduction

According to Ehrlenspiel et al. (2007), around 70 per cent of the costs for the market launch of a manufactured product are defined in the very early phases of the product life cycle. Thus, the design and manufacturing industry strives to pull decision points of high predictive quality upstream in the overall product creation process, increasing the pressure on the development departments to deliver faster, better and cheaper products, and thus to provide a competitive advantage for the organization (Baxter et al., 2008). Design automation (DA) has already been identified as a key enabler for addressing these challenges (Rigger et al., 2016). Two main leverages are used: On the one hand, automating routine and repetitive design tasks saves time and costs, and can be seen as achieving increased time for earlier stages of design processes (Skarka, 2007; Verhagen et al., 2012). On the other hand, supporting the early design phases by automatically exploring large and unstructured design spaces (Dym and Brown, 2012) and generating alternative design solutions (Chakrabarti et al., 2011) leads to improved product quality and shortened lead times (RQ2 in Section 5.1). However, there is a discrepancy between the availability of DA methods and their industrial application, especially regarding computational support of early design phases (Rigger and Vosgien, 2018). Reasons are uncertainties with respect to the awareness of available opportunities, recognition of potential of applying DA and ability to define the automation task (Bolognini et al., 2012; Rigger et al., 2016) (RQ1 in Section 5.1).

Thus, the motivation of the presented work is to help to increase awareness, understanding and adoption of DA solutions for the early stages of design processes, as such a support is still extremely under-leveraged in industry.

The paper contributes by presenting a systematic validation of design automation applications in design practice with a focus on evaluation of design automation opportunities for the early stages of the design process. To communicate potential for novel design automation applications (here early-stage design task automation), we put into context novel technologies with already existing ones (here later-stage design task automation).

We introduce an industrial case study concerning the design of ascent assemblies at Liebherr-Werk Nenzing GmbH (LWN). Two example cranes with ascent assemblies are shown in Figure 1. The DA tools used in the case study are a prototypical design space exploration tool generating a number of pre-optimized layout designs (Závoianu et al., 2018), and a product configurator, which is in operational use at LWN, to perform assembly configuration tasks mostly occurring during the detailed design phase (Frank et al., 2014). We approach the case study by developing an automation roadmap, i.e. modeling and comparing as-is and to-be processes:

- without any DA tools;
- with the product configurator only; and
- with the integrated product configurator and design space exploration tool (referred to as integrated workflow).
The success of the in-operational use product configurator (i.e. posterior to implementation) is validated using quantitative and qualitative assessments. For the prototypically implemented design space exploration tool, as well as the integrated workflow, a potential estimation and qualitative assessments including acceptance and usage prior to implementation are performed.

This paper argues that a combination of early and later process stage DA tools can, on the one hand, effectively meet typical industry requirements for DA, such as the reduction of lead times and error rates. On the other hand, the integration of a tool which generates a number of alternative layout designs (here crane ascent assembly paths) with a tool which automatically creates the detailed CAD ascent assembly models and respective production costs, bears the potential to evaluate and compare alternative, potentially novel optimal design solutions, and hence, to pull the decision-making to a relatively early point in the design process (again RQ2 in Section 5.1).

Section 2 positions our work regarding the current state of the art of DA and the limited application of DA solutions. Section 3 describes the approach for identification and estimation of DA potential before implementation and for industrial success evaluation after implementation. In Section 4, the case study for integrating DA solutions supporting the design of crane ascent assemblies in the early and later design phases is introduced. The results and the validation of the industrial evaluation of the two DA solutions as well as their seamless integration are presented in Section 5. In Section 6, these results as well as the potential to extend the introduced approach to a structured methodology for potential identification and success validation of DA solution are discussed. Finally, the paper is concluded in Section 7 with a summary and an outlook on future work.

2. Related work
2.1 Design automation

Two major communities of DA research can be identified, namely, knowledge-based engineering (KBE) (La Rocca, 2012; Verhagen et al., 2012; Stjepandić et al., 2015) and computational design synthesis (CDS) (Antonsson and Cagan, 2001; Cagan et al., 2005; Chakrabarti et al., 2011; Chakrabarti, 2013). Both investigate computational approaches to support design tasks by means of automation, and aim at improved reliability of predictions about states and features of future products and processes, before making decisions with a high impact on committed costs or other objective functions.

KBE approaches focus on the automation and streamlining of routine/repetitive design tasks predominantly occurring in later design stages and have their origins in knowledge based systems (Dym and Brown, 2012). Such design tasks are commonly characterized by
pre-structured solution spaces as, e.g. often occurring in the context of adaptive design (Pahl et al., 2007). KBE methods and tools tend to capture and deterministically automate already known best practice designs and can thus be termed conservative in nature.

CDS approaches aim at supporting early stages of design processes and can be termed systematically explorative in nature. Typically, large and often unstructured solutions spaces, such as more commonly occurring in the context of original design (Pahl et al., 2007), are explored using stochastic search strategies to generate a number of alternative, potentially novel designs. Thus, CDS aims at enabling and encouraging engineers to realize optimized designs beyond bias and by thinking out of the box. Furthermore, solution alternatives can be analyzed, compared and traded-off according to various design criteria, which can improve solution quality. As CDS methods are applied to support early design process stages, improved solution quality has potentially a very high impact.

2.2 Limited industrial application of design automation

The application of DA in industrial product development processes is still mostly limited to routine design (Verhagen et al., 2012) and redesign (Tomiyama, 2007) tasks, including the relative widespread use of configurators (Zhang, 2014; Willner et al., 2016). On the contrary, with a few exceptions only, successful applications aiming at design support in the early design stages remain limited to academic demonstrators validated by means of fictive case studies; industrial applications and evaluations are virtually absent (Bolognini et al., 2012) (again RQ1 in Section 5.1). Verhagen et al. (2012), Tomiyama (2007), and Bolognini et al. (2012) overview main reasons for DA project failures. By the presented case study we contribute to overcoming the following two reported reasons.

Firstly, systematically assessing a DA solution before and after its implementation is still a critical challenge for both industrialists and scientists. This is a key issue to lay the foundation for comparability, benchmarking and determination of return on investment (ROI) (Verhagen et al., 2015). Some guidelines on potential identification and justification are available (Stokes and Consortium, 2001; Emberey et al., 2007; van der Velden et al., 2012), but they are solely qualitative in nature, tend to focus on technological aspects, and are rarely and inconsistently applied (Verhagen et al., 2012). A first detailed approach to objectively quantifying automation opportunities for life cycle engineering tasks was introduced by Verhagen et al. (2015). The capability to assess and validate the added value of the deployed solution after implementation has been demonstrated by several case-based assessments (Shea et al., 2005; Singh and Gu, 2012; Emberey et al., 2007). However, there is still a lack of research on the practical implementation and adaptation in industry (Nordin, 2017). For such assessments, qualitative, quantitative, or mixed research methods can be used (Creswell, 2009). While engineers are more familiar with quantitative methods, qualitative ones can yield new insights, going beyond the findings achieved with quantitative methods (Daly et al., 2013), e.g. eliciting potential benefits as perceived by end-users (Hamraz and Clarkson, 2015). The combination of both prior and posterior evaluation, as well as qualitative and quantitative assessments is still open to be demonstrated.

Secondly, a particularly relevant reason of DA project failure mitigated in the context of this work is that DA often tries to achieve too many things at the same time, such as parametric design, optimization, data integrity management, process planning, and synthesis. As to this issue, it has been repeatedly noticed that besides a careful evaluation to find the right balance between manual and automatic design tasks, stepwise automation of well-defined design-process parts is often superior to overall full automation at once (Dym and Brown, 2012). This usually contributes to improved maintainability, re-use and adaptation of incorporated knowledge, and sustained usefulness and usability, because
users can use such DA tools in more flexible ways (RQ5 in Section 5.1). Additionally, the application and combination of different types of DA methods can be desirable. Recent approaches have mostly focused on combining a synthesis or configuration task with an analysis task to generate validated design alternatives of product architectures (Münzer and Shea, 2015), optimize topologies (Cui and Wang, 2013), or automate the generation of simulation models for calculated design configurations (Johansson and Elgh, 2013; Colombo et al., 2015). However, the combination of DA methods of early and later design phases to combine potentials and strengths of the methods has not yet been demonstrated and validated in industrial settings.

2.3 Identification of design automation potential and industrial validation
As mentioned in the previous subsection as the first barrier for implementing DA methods, one crucial aspect of DA projects is the identification and justification of the planned development effort prior to the actual implementation, adaptation or combination. This works towards being able to calculate ROIs of DA projects (Verhagen et al., 2015). However, demonstrating the added value of a DA solution before and after its implementation is still a critical challenge for both industrialists and scientists. Some guidelines on identification and justification are available (Stokes and Consortium, 2001; Emberey et al., 2007; van der Velden et al., 2012), but they are solely qualitative in nature, tend to focus on technological aspects, and are rarely and inconsistently applied (Verhagen et al., 2012), so not widely perceived to be useful.

Verhagen et al. (2015) introduce a method for the identification and justification of DA opportunities through quantification of information waste. The method is the first detailed approach to objectively quantify automation opportunities for life cycle engineering tasks.

Another important aspect of DA projects is the capability to assess and validate after implementation the added value of the deployed solution. Even though many studies have aimed at validating the usefulness of generative design systems through case-based assessments (Chau et al., 2004; Shea et al., 2005; Singh and Gu, 2012), there is still a lack of research on the practical implementation and adaptation in industry (Nordin, 2017).

One noteworthy approach is presented in Hamraz and Clarkson (2015), where it was preferred to conduct structured interviews for the qualitative assessment of their solution and to underline potential benefits as perceived by the end-users.

Unfortunately and as already mentioned by Verhagen et al. (2012), “these approaches toward the assessment of the suitability for automation of engineering tasks suffer from a number of shortcomings”. For instance, assessment criteria are often arbitrarily defined and it is not clear how these criteria are to be used in practice. Furthermore, the proposed criteria only allow for a qualified assessment of suitability for automation and usability, and adoption criteria are often omitted because they are difficult to define and assess. The present research work claims to demonstrate the opposite. Moreover, none of the mentioned related works address both the potential identification and the solution assessment posterior to implementation. Finally, in most of the cases the assessments are performed in a certain context for a specific case study and do not consider the assessment of the solution suitability in other contexts (e.g. preliminary vs detailed design, original vs adaptive design).

3. Approach
Our approach, illustrated in Figure 2, is divided into two main blocks: Block A is dedicated to the potential identification and assessment of DA tasks prior to implementation. Block B addresses the industrial assessment and validation of DA solutions posterior to implementation. The overall approach is based on standard analysis and design processes.
of workflow modeling towards process re-engineering (Sharp and McDermott, 2009). The four steps are explained below:

(I) In the first step, the as-is process of the design task at hand is established. The process can be derived from existing documentations and/or established from scratch by performing specific workshops with the engineers.

(II) In the second step, the corresponding to-be process is modeled.

(III) By comparing as-is and to-be processes and by using quantitative and/or qualitative assessments, the potential and expected benefits of DA solution are elaborated. For the quantitative assessment, metrics, such as lead-time reduction, can be derived from a list of DA drivers defined in Rigger and Vosgien (2018). Similarly, qualitative evaluation with end-users, e.g. by conducting structured interviews can be performed according to this list of motivational drivers, overall contributing to consistency of criteria. Generally, a qualitative assessment often complements a quantitative evaluation. In particular, qualitative evaluation is often used in exploratory parts of a study, whereas quantitative measures are often more appropriate for directed and more specific evaluation, e.g. in the context of results about acceptability and usability. Finally, an automation roadmap is established, summarizing the DA drivers and the gaps between the as-is and to-be processes.

(IV) Once a DA application has been deployed as a productive system (i.e. in operational use), the success validation can be performed.

Two ways of validation are distinguished:

(IV.1) **Quantitative assessment**: Here, the same metrics as already applied for potential estimation (Step III) are re-evaluated and compared.

(IV.2) **Qualitative assessment**: By conducting structured interviews and questionnaires with end-users, the process improvement is assessed and feedback, e.g. regarding usability and acceptance is gathered.

4. Case study: integrating design automation solutions for the design of crane ascent assemblies

Figure 1 shows an offshore crane and a gantry of a mobile harbor crane manufactured by LWN. The ascent assemblies, colored in red, are the external access structures required to
reach certain points/areas, e.g. for maintenance and steering. These points are termed access points. The composition of such ascent assemblies typically involves a set of standardized, parametrizable components (e.g. platforms, ladders, stair cases).

On the one hand, offshore cranes are standardized products realized in different variants. During the design phase, the re-use of components across these variants is ensured and the configuration and positioning of the ascent assemblies is subject to very few degrees of freedom. Updates to the design of crane and ascent assemblies are realized in regular, relatively long intervals. On the other hand, gantries are made of configurable main components, which are adapted according to the requirements of each customer, and the configuration and positioning of the ascent assemblies is subject to many degrees of freedom. Therefore, the potential for computational support of configuration and optimization will be studied in the context of original (offshore) and adaptive (gantries) design, respectively. RQ4 will be evaluated in this context.

4.1 As-is and to-be processes
Following the approach introduced in Section 3, first, as a baseline, the current as-is process was modeled separately by two persons from the technology management department. No major differences occurred. The modeling of the current as-is process was conducted again with all six engineers participating in the interview study. Again, no noteworthy differences were found, as this a well-defined, stable standard process. It includes the product configurator “Automatic Crane Component Design” (ACC-Design), which is in operational use and automates the rather repetitive and time consuming task of designing individual ascent assembly modules. Details can be found in Frank et al. (2014), a short summary is given in Section 4.3.1. Figure 3 (a) shows the current as-is process representing the description of the process steps, their sequencing, the input and output as well as the involved stakeholders.

The main inputs of the process are crane geometry, customer requirements and constraints, and existing standardized solutions of ascent assemblies. The final outputs are the “as-built” crane model including all geometrical and manufacturing details and the complete ascent assemblies and interface components between the ascent assemblies and the crane structure.

The process is decomposed into design phases known as preliminary (early) and detailed (later), where the preliminary one ends with the delivery of a final draft of a parametrized CAD model of the crane including preliminary ascent assemblies.

In the preliminary design phase, the processes for original and adaptive design differ: While for the original design, the engineers iteratively refine the crane design and adapt the ascent assembly components using ACC-Design, in the adaptive design, they sketch several and select one feasible layout for the ascent assembly and configure it based on this sketch in ACC-Design. In both cases, to verify and validate the generated ascent assembly solution, the engineers perform a clearance analysis in the CAD system to correct potential errors and inconsistencies in the model again using ACC-Design.

The detailed design process is the same for both adaptive and original design. First, the assembly CAD model is refined and completed with the appropriate standardized interface components (welding plates, bolted flanges, etc.) for mounting the ascent assemblies to the structure of the crane. Second, the manufacturing drawings are automatically generated in ACC-Design. The final step consists of choosing, refining and integrating the gratings of the various platforms.
The current as-is model is similar to the initial as-is model with the exception that the developed product configurator (ACC-Design) has been integrated in the process supporting the in green highlighted steps.

With regard to the to-be process, several potentials were identified in the baseline interviews with the technology management department (boxes highlighted in orange). This
was achieved, using the same, already mentioned set of drivers. In preliminary design, within the adaptive design, the drafting of the ascent assembly sketches could be automated and optimized. Within the detailed design phase, the repetitive tasks of adapting interface components and selecting the gratings bear automation potential. The potentials brought up in the interview study with the engineers are discussed in sections 5.1 and following.

4.2 Automation roadmap
In the baseline interviews, based on the comparison of as-is and to-be processes and the together defined automation roadmap, it was decided to prioritize the motivational driver “Generation of new design alternatives” by exploring the potential “Draw the ascent assemblies paths sketches”. Thereto, it was further decided to develop prototypical solutions for defining the layout/routing of the ascent assemblies, i.e. finding a path network connecting the access points. Their value will be evaluated by RQ3 as listed in Section 5.1. First solutions were recently prototypically realized, as elaborated by Zăvoianu et al. (2019), Hellwig et al. (2019), Zăvoianu et al. (2018) and summarized in Section 4.3.2. Besides improving the adaptive design process through this optimization, integrating the sketching functionality with ACC-Design bears the potential to further automate both the adaptive and original design processes (as elaborated in Section 4.4).

Building on these results and prior to any new automation/optimization deployment, the DA roadmap and a migration plan were validated, as illustrated in Figure 3(b): The first plateau corresponds to the initial as-is process without any implemented and deployed DA solutions. The second plateau corresponds to the current as-is process which is supported by ACC-Design. Finally, the third plateau represents the targeted to-be process in which ACC-Design is integrated with the path layout optimization algorithms. For the second plateau, the anticipated objectives for improving the initial as-is have been identified to be standardization, error rate reduction and lead-time reduction (purple boxes); for the third plateau these objectives are lead-time reduction, cost reduction and generation of novel designs, supporting the out of the box thinking.

4.3 Developed configuration and optimization solutions
The developed applications to automate and optimize initial and current as-is processes, respectively, are presented in the following two subsections.

4.3.1 Automatic crane component (ACC) design. The product configurator ACC-Design was developed to automate the cumbersome, time-consuming and error-prone detail design. Its implementation has been stepwise refined and extended, and is in operational use for a couple of years. Details can be found in Frank et al. (2014).

The application takes as input a set of standardized parts, a rule base for assembling these parts, and user input to define the particularities of the ascent assembly at hand (e.g. shapes and dimensions of platforms). Furthermore, the engineer defines how the assembly components (i.e. platforms, ladders and stair cases) are combined to obtain the complete ascent assembly. An inference engine processes this input to first represent it in a tree-based standard format before the CAD communication and generation modules send the information to the CAD system to generate the 3D-CAD model and the production drawings. Additionally, the bills of materials and the costs are inferred. In case the engineer needs to adapt the model, the inference engine includes the functionality to change and update the model based on modified user input.

4.3.2 Optimization of routing. Using ACC-Design, an engineer so far has to manually define how to dimension and combine platforms, ladders and stairs to form an ascent assembly. In this section, attempts to automate and optimize this task are presented. The
The implementation of these algorithms is on a prototypical level; details can be found in Zăvoianu et al. (2019), Hellwig et al. (2019), Zăvoianu et al. (2018).

In essence, it is assumed that a crane surface can be represented by a cuboid, which is unraveled to a 2D-plane, as shown in Figure 4(a-c) for a gantry of a mobile harbor crane. While this is a simplifying and rather restrictive assumption, the resulting algorithmic problem, namely, the Steiner-Tree Problem (STP) (Gilbert and Pollak, 1968), is NP-hard (Garey et al., 1977). The STP consists of finding the shortest path among a set of predefined terminal nodes (in our case the access points), with the option of freely placing additional nodes (the so-called Steiner points) to reduce the length of the overall path. For NP-hard problems, applying genetic algorithms for searching the design space is a viable way for finding optimal design solutions. This approach is taken in all three mentioned papers.

For brevity, we focus on the algorithm presented by Zăvoianu et al. (2019, 2018). The cost function of the optimization is to minimize the Euclidean distance of the path with optional penalties for violating certain angle restrictions (e.g., penalizing angles other than 0°, 45°, and 90° to achieve designs realizable with standard components) as well as for crossing obstacles. Instead of the Euclidean distance, any other measure of costs, e.g., in form of monetary costs, could be considered. Two solutions are shown in Figure 4(d): the left image shows the shortest path without any angle-restrictions, resulting in partly very steep inclination angles, i.e., very steep, non-manufacturable stair cases; the right image shows the solution for imposing angle constraints of 0°, 45°, and 90°.

The optimized ascent assembly may be restricted to be fully connected, or be divided into several disjoint components, in which case the algorithm chooses automatically the optimal point to split the ascent assembly (to minimize the costs). Two examples are shown in Figure 4(e).

Finally, the inclusion of a second, conflicting objective function was realized, to be able to trade-off solutions, e.g., with different angle restrictions along the so-called Pareto-front, as shown in Figure 4(f) for solutions with no angle restrictions and solutions with imposed restrictions of 0° and 90°.

4.4 Towards a seamless integrated design automation workflow
The integration of the two applications introduced in Section 4.3, as illustrated in the 5 steps of Figure 5(a), would further automate the ascent assembly design process towards improved leverage of the following potentials: Reduce lead time, reduce costs, and discover and realize new designs. This line of development extends the potential of automatically drawing the ascent assembly's paths sketches. It was performed based on the initial optimization prototype developments and before the industrial evaluation presented in the next Section, towards also evaluating RQ6 as listed in Section 5.1.

The current status of the 5 steps regarding implementation are indicated in Figure 5(a) by the green and purple boxes: Step 1 and 3 are on an idea level with feasibility checked, for Step 2 and 4 a prototypical implementation exists (i.e. step 1-4 are prior to implementation according to the approach of Section 3), and the software of Step 5 is in operational use (i.e. post implementation).

In the first step, starting out from the CAD model of the crane or gantry, the dimensions, corners as well as access points and obstacles have to be defined and translated to the 2D representation. Currently, the representation of the 2D abstraction is generated manually. For semi-automatic generation, a user interface could be developed in which the engineer enters the required data (access points, crane corners, obstacles), and the translation is done automatically. Alternatively, the engineer specifies the points directly in the CAD model, which are then automatically extracted to generate the 2D representation. This
representation is stored in a pre-defined standard format, which serves as input file for the optimization algorithms.

Secondly, any of the presented optimization algorithms of Section 4.3.2 is applied to the 2D representation to infer a path between the access points while avoiding obstacles. The algorithm outputs another file containing the network representing the assemblies. Alternatively, the design engineer could draw the routing manually on the 2D plane.

In the third step, the solution(s) of the optimization algorithm are presented to the design engineers who can verify and post-process the solution(s) according to their standards. Post-processing options for the deployment include moving, adding and deleting access points and obstacles, pulling the lines of a solution of the output of the algorithm, interact

Figure 4.
(a) A gantry of a mobile harbor crane; (b) 3D representation of the gantry by stacking two cuboids on top of each other with blue dots depicting access points and red rectangles obstacle areas; (c) unfolded 2D representation of the gantry with grey areas representing non-accessible spaces, which are treated as obstacles; (d) solutions with one entry point and different angle restrictions: left – no restriction; right – 0°, 45° and 90°; (e) solutions with two entry point and different angle restrictions: left – no restriction; right – 0°, 45° and 90°; (f) multi-objective optimization results when trading-off geometrical/Euclidean optimality and domain-specific optimality (featuring only 0° and 90° angles).
with the optimizer in terms of modifying the solution and re-starting the optimization, as well as running a multi-objective optimization and selecting from several results. The post-processed solution network is stored into a file, which is used as input for translating the lines to ACC-Design.

In the fourth step, the post-processed network is analyzed and translated to an XML-file, which contains assembly and assembly combination information in the format specified for ACC-Design input files. During the translation process, restrictions imposed by ACC-Design, e.g. that certain combinations are not possible (such as directly connecting a ladder to a stair case without a platform in between), are handled.

Finally, in step five, the generated XML-files are opened in ACC-Design. The engineers can now verify the input and adapt settings not related to the dimensions, such as the safety cage of the ladders or the stability of platforms (e.g. standard or extra strong), and generate the ascent assembly draft.

5. Industrial evaluation
An interview study was conducted with six engineers, distributed evenly on the two departments for designing ship- and offshore cranes (original design) and mobile harbor cranes (adaptive design). The interview study included an assessment of benefits/potentials and limitations of ACC-Design after implementation and of the optimization and integrated workflow before implementation, as well as questions about acceptance and usage of the integrated workflow, and DA solutions in general.

Towards this end, the integrated workflow procedure was explained to the interviewees on a conceptual level with a figure similar to Figure 5(a), the optimization using figures

![Figure 5](image-url)

Sub-figure (a) shows the integrated automation workflow of ascent assembly design, (b) the abstract representation and generated ascent assembly of the expert solution using the workflow and (c) an optimized solution with angle restrictions of $0^\circ$, $45^\circ$ and $90^\circ$ and the generated ascent assembly (only larger component of the CAD-model is shown).
similar to the ones in Figure 4, and the interaction/post-processing within Step 3 as a list of options with explanations. For Step 4, the translator was first explained on a conceptual level, and after an initial judgment, the prototypical implementation was shown to validate the effect of a prototype demonstration. Finally, the complete workflow was demonstrated by showing the engineers the expert solution in the abstract representation and the generated 3D-CAD model inferred by the prototype translator as shown in Figure 5(b), as well as several solutions of the optimization algorithm with two entry points and varying angle restrictions, one of which is shown in Figure 5(c).

5.1 Research questions

The following research questions (RQ) evaluated in the following are derived and have been made explicit at different passages beforehand. They focus on early-stage DA support and seamlessness.

RQ1. (Early-stage DA uncertainties): Will it again appear that there are uncertainties with respect to the awareness of available opportunities, recognition of potential of applying DA and ability to define the automation task (Rigger et al., 2016)?

RQ2. (Early-stage DA value): What is the value of early-stage DA in this context?

RQ3. (Prototypes value): What is the value of demonstrating new functionality with prototypes?

RQ4. (Optimization suitability): Will the path layout optimization be more suitable to early-stage original design or early-stage adaptive design in this context?

RQ5. (Control vs full automation): Do designers value more control and decision-making vs fully automated design tasks, or vice versa?

RQ6. (Seamlessness): What aspects of seamless integration of DA tools do designers value?

5.2 Potentials/benefits and limitations

For the qualitative validation of the potentials/benefits and limitations of the integrated workflow and its components the interviewees could, on the one hand, pick pre-defined answers from a list of drivers for design automation and optimization deducted from an interview study among about 50 manufacturing companies (Rigger and Vosgien, 2018). On the other hand, to gain deeper insights and to double check the answers, open questions regarding the benefits and potentials were posed. These answers were structured according to the list of drivers, and, to fully reflect the participants’ answers, the list was enriched with additional criteria (in particular enhanced change management, in terms of detecting required changes and propagating them, as well as reproducibility). While Steps 1 to 4 of the integrated workflow were assessed qualitatively before implementation (corresponding to Step III of the introduced approach), Step 5 was largely validated qualitatively after implementation (corresponding to Step VI.II), but also a limited quantitative success validation (corresponding to Step IV.I) on time savings was performed by extracting lead times from the ERP system. The results are summarized in Figure 6. They are all based on the already mentioned same set of motivational drivers.

Overall, with regard to the expected benefits of the complete workflow, the quick solution generation, which enables the development of customer specific designs, would become even more easy by connecting ACC-Design to the optimization. In Steps 1 and 3, change
management is supported by moving, adding and deleting access points in the abstract representation, which also helps in reacting fast to changes in customer requirements. A straightforward potential of Step 2 is to reduce costs by finding a shorter/cheaper ascent assembly solution. However, the biggest benefit of the optimization algorithm, emphasized by all of the adaptive design interviewees plus one other, lies in the generation of alternative, potentially novel solutions, by using a multi-objective optimization, setting appropriate angle restrictions or varying the number of entry points. Seeing between two and five solutions would help the engineers to faster select a concept because there is less need to search for previous solutions. This also means that the knowledge of how to route the ascent assembly would be stored in the algorithm, i.e. preserved independent of the engineers. With this regard, it was, e.g. positively observed by the interviewees that the solutions with two entry points of the optimization algorithm (Figure 5(c)) inferred the same splitting point of the ascent assembly as the expert solution (Figure 5(b)). While for the experts the reason for the splitting are because of mounting considerations (possibility to mount part of the assembly...
later), the optimization algorithm looked for the shortest possible solution. All of this is directed at answering RQ2. Potentials identified in Step 3 are particularly addressing RQ5: the potential of enhancing change management and faster reacting to changes of customer requirements, as discussed together with Step 1, is further enabled by post-processing a solution (e.g. pulling lines), which helps in correcting and updating a solution. For example, the ascent assembly inferred by the algorithm without any angle restrictions (left image of Figure 4(e)) could not be directly generated in ACC-Design because too short and too steep stair cases were contained in the network. Establishing a knowledge base could also be part of the post-processing, e.g. by only allowing certain changes when pulling the lines. The translation of the network to ACC-Design in Step 4 was perceived as very positive by all interviewed engineers. They see the potentials to save time and reduce errors, as it automates a rather cumbersome task. These two potentials also yield a cost saving potential as well as the possibility to react faster to changes of customer requirements. This relates to RQ6.

Finally, the evaluation of ACC-Design posterior to implementation revealed a rather long list of benefits, including all drivers initially listed in the automation roadmap. For the implementation of ACC-Design, the parts and their assembly procedures were standardized. Thereby, the designs’ consistency was improved, costs reduced (fewer parts need to be managed) and error rates decreased (especially through the incorporation of company and industrial norms and standards as well as the automatic selection of structurally appropriate components; these points were mentioned as large benefits by all engineers). The automation further resulted in the establishment of a knowledge base, enabled the re-use of this knowledge and lead to reproducibility of the results, as the design procedure, norms/standards and structural calculations are stored and applied to every new design, which helps in understanding and trusting the solution. Finally, lead-time reduction (reduction of time spent for repetitive tasks - time savings) is especially achieved through the following three points:

1. As highlighted by several engineers, automatically obtaining a draft and detail design including the CAD model and production drawings (i.e. visualizing designs and generating documentation) eliminates the time-consuming search for suitable parts.

2. The ability of updating the design using the update-functionality of ACC-Design enhances change management allowing to correct inaccuracies and faster react to changes in customer requirements.

3. Integrating norms and structural requirements in the product configurator supports the norm/standard checking tasks and replaces time-intensive calculations.

For the quantitative success validation, as mentioned in Frank et al. (2014), up to 90 per cent of the overall design time can be saved by using ACC-Design. For a more detailed analysis, lead times were extracted from the ERP-system revealing that an average overall reduction of about 50 per cent is achieved, with roughly 30 per cent of time being saved in the early design phase and almost 60 per cent in the detail design phase. As stated by several engineers, the saved time can be used to improve the solution quality, offer several solutions and hence better meet the customer requirements.

For the drawbacks of the overall workflow, the current application area seems to be rather restrictive (require crane surface which can be unrolled), and only minor time and cost savings are expected when considering the complete workflow. This of course questions the ROI of such an implementation. One major reason for these limitations is the 2D representation (Steps 1 and 2). All engineers agreed that for an actual implementation, the representation would need to be in 3D and automatically generated from the CAD model.
(such that changes in the CAD model are propagated to the abstract representation). Here, the idea level with only the feasibility checked produced an artefact to be overcome. With regard to the optimization algorithm in Step 2, some further limitations were seen, related to RQ2. The main point of criticism was the extensive use of ladders: In practice, there is an important distinction between main ascent assembly components (used almost daily) and side ascent assembly components (used at most a few times per year for maintenance), where the former should consist of stairs and platforms only, and the latter may well additionally contain ladders. This distinction is currently not made in the algorithm. Furthermore, access points are not always strictly given as exact points, rather they are picked from a certain access area. Often, solutions between different cranes/gantries should look alike (e.g. when several cranes/gantries are installed next to each other), meaning that the optimization, even though it could find cheaper results for some of the cranes/gantries, is not required. Also for the post-processing in Step 3, some restrictions should be enforced, such as the distinction between main and side ascent assemblies (addressing RQ6). Solely for Step 4, i.e. RQ6, no limitations were mentioned.

With regard to the limitations of ACC-Design in Step 5, for certain specific use-cases, ACC-Design cannot handle the required exceptions (e.g. forcing a stay at a specific position, as these are placed in an optimally spaced distance) and manual fine tuning is required. For quickly drafting a solution it had been good to exclude all small parts (e.g. screws) when generating the CAD model. However, for the detail design, exactly this feature is required. ACC-Design also does not feature a functionality to search for already generated assemblies (in previous projects), which would further assist in re-using not only parts but also assemblies. Finally, as highlighted in Figure 3 (a) in the detail design process, the red boxes also bear potential for improvement and could be included as additional functionalities in ACC-Design. On the one hand, weld-on plates for attaching the ascent assembly to the crane have to be manually adapted (because the distance information between crane and ascent assembly is not known in ACC-Design) and other weld-on and bolted parts for e.g. attaching cables and lights have to be added manually. Especially with regard to the last group of parts, adaptations made via the update function of ACC-Design do not apply to these parts. On the other hand, after finishing the drawings, gratings have to be added to the platforms, which includes a manual search for similar parts; this is also a cumbersome task not covered by ACC-Design and a candidate for automation.

5.3 Acceptance and usage
Regarding the integrated workflow, as Steps 1-4 are not yet in operational use, an evaluation focusing on potential usage and acceptance has been conducted. The validation of the targeted integrated automation workflow is divided into four parts: overall evaluation, optimization, interaction, and seamlessness. The interviewees were posed several questions, which they were asked to rate according to a five-tier scale and comment on their ratings. The questions and answers are shown in Table I (top table). The results for original design (ship- and offshore cranes) and adaptive design (mobile harbor cranes/gantries) differed for certain questions, and are hence shown separately.

With regard to the overall evaluation of the workflow, the interviewed engineers were mostly positive, seeing the sense of such a workflow integration, believing that it could work and being open to use it, naturally under the condition that the solutions are meaningful. For use cases with little degrees of freedom (such as in the original design) the application seemed less realistic to be useful, but for other application areas, also these engineers stated that they can well imagine that it supports the work, addressing RQ4.
With regard to the optimization, the current intention to use such a tool is not very high, the reasons for which are three-fold (addressing RQ2):

1. For the original design, the concept of routing the ascent assembly has to be defined simultaneously to design the crane itself because of strict space restrictions leaving almost no degrees of freedom to choose a routing.

2. For the adaptive design, even though there are significant degrees of freedom, a concept is defined rather quickly, and hence, there is no immediate time gain when using an algorithm.

3. In general, there are missing restrictions in the algorithmic implementation, such as the distinction between main and side ascent assemblies.

However, defining a routing manually on an abstract representation is perceived as a useful way of making drafting easier in both original and adaptive design. Regarding the trust in an optimization solution, the interviewees responded that it grows with seeing useful solutions. The engineer who responded to rather not use the solution could not imagine that it is accurate enough to fulfill all the required space restrictions. Lastly, the run-time of the optimization was also of different importance, ranging from instant to “half an hour or more, if the solution is good”.

Addressing RQ5, the importance of interaction possibilities was rated very high for actually using such an application, especially for post-processing the solution network (pulling lines), but also in terms of moving access points and obstacles to be able to react to changes in the surroundings. An important aspect was the connection of the CAD-model of the crane/gantry to the abstract representation, such that any changes (e.g. moving the cable reel) are propagated automatically (RQ6, consistency, change management). The interaction with the optimizer itself was less popular, and also only under the restriction, that made changes (e.g. pulling a line in a certain place) are not adapted anymore by the optimizer.

Addressing RQ3, 4 and 5, the selection from several solutions was judged very useful, especially in terms of trading-off solutions only containing stair cases and solutions also allowing ladders. Here, consistently to the explorative identification of potentials as to Step 2, the generation of alternative solutions is evaluated most useful.

Finally, with regard to the seamlessness, i.e. the integration of the optimization and ACC-Design, the usefulness especially of the translator of Step 4 was recognized and acknowledged (again addressing RQ6). For the same reason, the workflow was judged to increase the value of ACC-Design. As stated above, before the first judgment, the translator was only presented on a conceptual level, to evaluate the effect of showing a working prototype. The answers to the above questions did not change after seeing the prototype. However, for most engineers, the demonstration of the prototypes left a positive impression, making the idea more concrete and showing its applicability. Furthermore, running prototypes raised trust and, although not evaluated, seemed to improve recall.

To obtain more general statements about the acceptance and usage of automation/optimization applications, we asked the engineers to rate certain criteria from a general point of view, and comment on their judgment. The results are shown in Table I (bottom table).

The two most important factors for accepting a design automation or optimization application are the practical relevance (i.e. appropriateness of the tool for the task at hand) and the possibility to influence the solution finding (again answering RQ5 in the same direction as before), closely followed by trusting and understanding the solution. While a stepwise introduction and seeing/testing the application beforehand with a prototypical
Table I.
Top table: overall workflow evaluation, separately for the original (“orig.”) and adaptive (“adapt.”) design tasks including average ratings (“Av.”).

<table>
<thead>
<tr>
<th>Question</th>
<th>Design</th>
<th>Evaluation</th>
<th>Av.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overall evaluation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Does it make sense?</td>
<td>Orig. 1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Do you think it works?</td>
<td>Orig. 1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Would you use it?</td>
<td>Orig. 1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td><strong>Optimization</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Would you use it?</td>
<td>Orig. –1</td>
<td>–1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Adapt. 1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Would you rather draw the path manually?</td>
<td>Orig. 2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Would you trust it?</td>
<td>Orig. 1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Would you use the proposed solutions?</td>
<td>Orig. 1</td>
<td>–1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Does run-time need to be instant?</td>
<td>Orig. 2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 2</td>
<td>–1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Interaction</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In general?</td>
<td>Orig. 2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Adapt. 2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>For moving access points and obstacles?</td>
<td>Orig. 1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Pulling lines?</td>
<td>Orig. 2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Adapt. 2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>With the optimizer?</td>
<td>Orig. 0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Selecting from several solutions?</td>
<td>Orig. 2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Seamlessness</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is the integration of optimization and ACC-Design important?</td>
<td>Orig. 1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Does this workflow increase the value of ACC-Design?</td>
<td>Orig. 2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Adapt. 2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Bottom table: General evaluation of acceptance and important aspects for design automation and optimization applications. Scale: –2 (absolutely no), –1 (rather no), 0 (neutral), +1 (rather yes), +2 (absolutely yes).

<table>
<thead>
<tr>
<th>Question</th>
<th>Evaluation</th>
<th>Av.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acceptance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Practical relevance</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Stepwise introduction</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Stepwise integration of users</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>See/test prototype</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Trust/understand solution</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Influence solution finding</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Aspects</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Functionality</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Usability</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Comprehensibility/traceability</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Seamlessness</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
implementation does not seem to be a crucial aspect for the acceptance, the stepwise integration of the users in its development is. Here, several of the interviewees pointed out that key-users should be integrated in the development phase, especially for determining the required input and the expected output, and with a growing integration the further the development is.

When asked about various aspects of a DA application, usability and functionality were rated the highest. With regard to functionality, an engineer stated that first of all frequently performed tasks with a wide user circle should be automated. They also appreciate small tools, which facilitate or support their daily work, and prefer add-ins for the used program (e.g. the CAD-system) over stand-alone applications, as this facilitates the usage. This explains the seemingly surprising order of ratings for functionality and usability. This again answers RQ5 consistently. The importance of comprehensibility/traceability ranged from very important to neutral. While for some engineers it was most important that the resulting solution looks reasonable, others required to understand the w2ay the solution was found especially when starting to use a tool. Seamlessness was also judged to be of varying importance: Lower ratings were commented with the usefulness of small supporting tools facilitating daily work (emphasizing the control aspect of RQ5), and higher ratings with the importance of connecting DA application to the CAD- and PDM-system (emphasizing automatic synchronization of data as to RQ6), tremendously simplifying work and helping in standardization.

5.4 Study validation
According to (Robinsons, 2016; Venkatesh et al., 2013), there are two primary validation issues, roughly analogous for quantitative and qualitative evaluation, i.e. reliability and validity of measures.

As to the approach adopted, it is based on standard workflow modeling in the context of process re-engineering/improvement. As-is processes have all been consistently produced. The potentials/benefits and drawbacks have all been evaluated based on the same set of motivational drivers as explained before (although with some extra extensions from open questions), where qualitative evaluation was first performed for exploratory purposes, yielding consistency in Figure 6. Afterwards, for more detail, the quantitative results in Table I have been acquired. Both Figure 6 and Table I have been given to the study participants for double checking after the study and before submission of this paper. Although this doesn’t ensure exact measurement reliability, it works towards consistency. During all the interviews, the values displayed in Table I remained the same before and after prototype demonstrations as compared to conceptual explanations of the 5-steps workflow.

While external validity of the answers of the research questions is already framed by the text passages they are derived from, further validation is as follows:

RQ1. (Early-stage DA uncertainties): Indeed, there are again uncertainties found with respect to early-stage DA with a major exception of “generation of alternative solutions” in Figure 6 and “selecting from several solutions” (in particular for adaptive preliminary design) in Table I. The latter consistently achieved maximum rates.

RQ2. (Early-stage DA value): Overall, the highest value of early-stage DA is in what is emphasized in RQ1. Thus, the validity argument is the same as for RQ1.

RQ3. (Prototypes value): Although for both results sets (Figure 6 and Table I), the answers didn’t change in reaction to prototype demonstration, we argue that without prototype implementation, neither the optimization results could have
been presented in such detail nor the integration in the five-step procedure would have emerged so concretely. Nevertheless, the internal validity of this statement cannot be proved high.

**RQ4.** (Optimization suitability): The path layout optimization is more suitable to early-stage adaptive design in this context. This is demonstrated with very high internal validity by all the relevant average values of the top table of Table I consistently showing higher ratings for adaptive design than for original design.

**RQ5.** (Control vs full automation): Designers value more control and decision-making vs fully automated design tasks in the given context. Overall, this is a trade-off relationship. In this study, however, as can be seen in the interaction segment of the top table of Table I, it can be validated that it is control preferred over full automation. In particular, interaction with the optimizer is rated lower than choosing from its results. This is further supported by the answers regarding clear scoping of often smaller DA tools over full/seamless process automation.

**RQ6.** (Seamlessness): The dominant aspect to the participants of the study is the translator from 2D to 3D. Such translators are commonly used in all kinds of model-based design approaches. However, seamlessness doesn’t appear to be a value in its own, but only supportive.

The validity of the answers to **RQ1 to 6** are further substantiated by the discussion and conclusion, which have both been evaluated as correct by the industrial study participants.

### 6. Discussion

The results of the industrial evaluation and discussion are based on the opinions of the interview participants; any generalization would require further investigations and validations. The interviews were conducted by the developers of the integrated workflow, which allowed the interviewees to ask questions in case of lack of clarity, but could have distorted the assessment due to the missing anonymity.

Assessing in-use tools after implementation cannot only be used to evaluate these tools (in our case ACC-Design, Step 5 of the integrated workflow), but also help in gathering ideas for further lines of developments (e.g. automating adjustment of weld-on/bolted parts) because during such a validation limitations as perceived by the end-users are revealed. Similarly, by validating ideas and prototypes before the actual implementation (in our case Steps 1 to 4 of the workflow), important directions of developments can be identified and corrected early on (e.g. option to draw sketches manually; extension to 3D). Towards this end, showing engineers solutions generated by the prototype not only left a positive impression, but especially helped in extracting implicit knowledge about the design of ascent assemblies (e.g. main vs side ascent assemblies, access points vs access areas).

The rather critical validation of the optimization itself can be mostly reduced to three reasons. (1) The use cases were on extreme ends of the application range: While solving the routing problem for gantries is a rather easy task, for ship- and offshore cranes, it is intertwined with the crane design itself, leaving little to no room for optimization. Thus, time and cost saving potentials were also judged to be minor. The engineers, however, acknowledged that a similar algorithm could be useful for routing pipes, tubes, ropes or cables, where the problem solving is more involved. (2) The 2D representation, on which the algorithm operates, is in practice simply too restrictive (not enough application areas) and unconventional (engineers mainly work in 3D), even if it is from a theoretical point of view very interesting and challenging to solve. Thus, for a proof-of-concept, the 2D representation...
is a valid starting point, and the algorithms are implemented in a way such that a
generalization to 3D is rather straightforward, but could come with increased runtime. (3)
Not all practically relevant restrictions are incorporated in the algorithms (e.g. main vs side
ascent assembly, access points vs access areas), leading to unfeasible results.

On the other hand, the generation of several solutions using the optimization was highly
appreciated among the participants, as it supports ideation of problem solving. This is
counter to the answers given to the acceptance and usage assessment from a general
perspective, where engineers were still most interested in automatizing repetitive tasks, and
also contrary to the results of the study in Rigger and Vosgien (2018), where obtaining
alternative solutions was ranked as a minor driver for implementing DA. This discrepancy
can be explained by the fact that only regarding the former part the engineers have seen an
approach for finding several solutions before answering the questions. Thus, engineers are
open to such approaches, however, do not seem to see the potentials themselves. Therefore,
well scoped prototypes seem an essential ingredient of potential evaluation. This is in line
with observations of the literature, where it is stated that DA practitioners are often not
aware of the available opportunities (Bolognini et al., 2012), do not recognize the potential of
applying DA (Verhagen et al., 2015) and lack the ability to select and implement appropriate
methods once the automation task has been defined (Amen et al., 1999).

The answers of the assessment prior to implementation point in the directions that
engineers prefer applications where the design task itself and the final decision-making are
left to the engineers. This is supported by three statements:

1. The option of replacing the optimization result with a manually drawn sketch was
perceived as very useful, especially when connected to the automatic translation of
the network to ACC-Design, also facilitating loops between the abstract and
concrete representation.

2. Allowing the designer to choose from several solutions was highly appreciated.

3. Influencing and post-processing the solution within the workflow was of great
importance.

These aspects allow to overrule the application’s solution, making the engineers feel useful and
needed. Furthermore, it helps in ensuring that the final solution is not blindly accepted and that
the engineer, potentially after adapting it, checks and confirms its feasibility. Thus, the
integrated workflow is appreciated for being a supporting tool rather than a tool automating
the complete design task, which is in accordance to the statement of (Dym and Brown, 2012)
that stepwise automation of well-defined parts is often preferred over full automation.

Based on the results and their discussion, the decision-makers obtain a profound basis for
determining further development steps and directions. This process is currently on-going.

The findings reported in Section 5 and discussed above have proven the applicability of
the approach introduced in Section 3, even though it was not entirely applied to one single
DA application and only with a minor quantitative assessment. Through the systematically
derived assessment criteria of Rigger and Vosgien (2018) and their case-specific
enhancement, not only the suitability and effectiveness of the solution were addressed, but
also acceptance and usage aspects. While such a generic set of assessment criteria for DA
tasks guides and supports the validation steps and enhances comparability of methods
when searching for appropriate DA methods for a given DA task, these criteria also need to
be refined specifically for the addressed problem and the chosen solution.

The used approach is a starting point for developing a generally applicable, systematic
methodology. Regarding Steps I and II and the identification of measurements in practice, a
more comprehensive systematic that not only considers design processes as to a task
precedence model (Wynn, 2017), but also takes into account the supporting tools and
technologies needs to be developed. This permits definition of design performance
assessment also from a software quality point of view such as usability.

In this context, first steps have been taken to appropriating long standing traditions in
usability engineering to a DA tool context. Role models were heuristic evaluation and
discount usability engineering, showing in a scientifically substantiated way good coverage
with only five participants, in particular as to exploratory studies (Nielsen, 1994).

7. Conclusion

The presented case study for ascent assembly design was used to demonstrate the approach
for validating previous and future developments, i.e. assessing the success/benefits and
potentials, respectively. The industrial evaluation after implementation of the KBE-
application ACC-Design (partly based on lead times with and without ACC-Design as
documented in the ERP of LWN) and before the implementation of the routing optimization
and the seamless workflow integration of the two applications were conducted by
interviewing engineers. Even though the complete approach introduced in Section 3 was not
applied to one single DA solution, the case study and the results of the interviews clearly
demonstrate the applicability of the approach, in particular by structurally assessing the
(expected) added value of different kinds of DA solutions.

The results of the evaluation of ACC-Design revealed that not only the anticipated
benefits (standardization, error and lead time reduction, as marked in Figure 3(b)) were met,
but additionally a couple more, not immediately sought for benefits were achieved. On the
other side, for the integrated DA workflow connecting the optimization with ACC-Design,
the evaluation prior to implementation points in the direction that not all anticipated
benefits are realistic. However, the possibility to generate several solutions was greatly
appreciated by the engineers.

This last point closely links to the central motivation of the paper - increasing the
awareness, understanding and adoption of DA applications in early design stages. While the
interviewees themselves see most improvement potential in repetitive/routine design tasks,
onto the idea of obtaining several solutions early in the design process was prototypically
demonstrated, it was very appealing, especially when connected to the existing, well-known
product configurator. Thus, by using prototypes, the awareness of what is possible is raised,
and with it the acceptance of such solutions.

Based on the above observations, the results of the interview study as well as the
discussion, there are several lines of future work:

- The restrictive 2D representation has to be extended to 3D for operational use, and
  with it the automatic generation of this representation from the CAD model should
  be realized.

- There are several extension that would enhance the practical relevance of the
  optimization algorithms: When using a 3D representation, also the algorithm needs
to be adapted to 3D, which is rather straightforward because of the flexible
implementation. Further restrictions should be incorporated in the algorithm, such
as the distinction between main and side ascent assemblies (e.g. by penalizing
 unwanted connections such as ladders along certain paths) or allowing access
points to be placed within an interval (e.g. heuristically by running the current
algorithm in parallel with different placements). Finally, for post-processed
solutions, the algorithm should include the option to not alter certain paths, e.g. by setting the costs for these paths to zero.

- In the presented workflow, an option could be introduced to choose between running the optimization and manually drawing the network sketch. For manual sketching, instead of generating a 2D/3D representation, the routing could be defined directly in the CAD model and translated to ACC-Design.

- Further automation potential was identified for some routine tasks in the detail design following the presented workflow, in particular for defining and re-finishing welding and mounting components, as well as searching for suitable gratings for the platforms. These are typical routine tasks that could be automated or at least computationally supported.

- Finally, the presented approach should be extended and generalized to serve as a general methodology for design automation potential identification and validation using both qualitative and quantitative assessments before and after implementation. Towards this end, DA templates and metrics have to be further developed and integrated into the methodology, and the entire method has to be applied to a single case study.

References


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Microscoping the challenges of sustainable construction in developing countries

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Abstract

Purpose – This paper aims to present the result of an assessment of the challenges of sustainable construction (SC) in two developing countries (Nigeria and South Africa). This was done with a view to improving sustainable project delivery, which is a problem among most developing countries.

Design/methodology/approach – The study adopted a quantitative survey approach with questionnaire used as the instrument for data collection from quantity surveyors, construction and project managers from both countries. Data analysis was done using a four-step analysis approach and relevant descriptive and inferential statistics were adopted.

Findings – The study revealed a considerable level of awareness of SC and involvement in the use of the same among the assessed professionals. Also, it was discovered that SC materials are mostly used in the aspect of surface finishing and masonry construction. Further findings revealed that resistance to change, client’s preference, fear of the increased cost of investment and inadequate knowledge and understanding of the concept of sustainability are some of the major challenges of SC in these countries.

Originality/value – The strength of this study lies in the assessment of happenings from two developing countries and its recommendation can to a large extent promote improved SC in developing countries particularly in Africa where construction activities are similar.

Keywords Nigeria, Sustainability, Sustainable construction, South Africa

Paper type Research paper

Introduction

In recent times, the construction industry has been a key contributor to the development of every country. The influence of the industry in promoting economic growth in every nation has been well-documented (Anaman and Osei-Amponsah, 2007; Chitkara, 2004; Construction Industry Development Board, 2012; Håkansson and Ingemansson, 2013; Leibing, 2001). However, despite the immense contribution of the construction industry to the development of nations, the industry in both developed and developing countries around the world is believed to be impacting negatively on the environment. Evidence of this can be seen in land degradation, high energy consumption and pollution being experienced in recent times (Du Plessis, 2002). According to Baloi (2003), while the construction industry is crucial in the social and economic growth of any country, its activities contribute heavily to unsustainable development and its impact on the environment is disturbing. Ametepey and Aigbavboa (2014) also noted that there has been clamor among scientists and scholars, that the rate, at which the earth’s resources are being consumed, erodes the earth’s support system.
To reduce the undesirable effect of the activities of the construction industry on the environment, sustainable construction (SC) thinking was proposed as a way of making the construction processes, activities and practices more economically, socially and environmentally responsive (Abidin, 2010). Introducing SC became necessary because of the need to secure the future generations ability to meet their needs by adopting sustainability principles in meeting present needs (Brundtland Report, 1987). To achieve this feat, the use of SC materials has become imperative in the delivery of construction projects. Miyatake (1996) has earlier suggested that for a sustainable built environment to be achieved, the construction industry must change the process of construction from linear to cyclic; where life to life process is assumed.

Construction in most developing countries has been adjudged to be unsustainable, judging from the three sustainability dimensions of social, environment and economy. Studies of Alabi (2012) in Nigeria, Al-Sanad (2015) in Kuwait, Baron and Donath (2016) in Ethiopia, Djokoto et al. (2014) in Ghana, James and Matipa (2004) in Zambia and Saad (2016) in South Africa all point to the poor level of SC practices in these respective developing countries. Equally studies have emanated on perception, awareness and ways of improving SC (Abolore, 2012; Miranda and Marulanda, 2001) barriers of SC adoption (Aghimien et al., 2018a; Aigbavboa et al., 2017; Ametepey et al., 2015; Djokoto et al., 2014) renewable energy, energy efficiency and green buildings (Aghimien et al., 2018b; Ahmed and Gidado, 2008; Isa et al., 2013) and management tools in delivering SC (Oke et al., 2015).

Despite the availability of these studies, construction in developing countries has failed to improve in the delivery of sustainable projects with old practices and materials still being used. Thus, the questions that remain pertinent are; are SC materials readily available in developing countries and to what extent are they being used? What are the impediments to their proper and constant usage? This study place focus on the latter. Reason for this is that through proper understanding of the challenges of SC, measures towards eliminating these challenges and achieving better SC projects can be developed. To give an answer to this question, understanding the perspectives of those involved in the procuring and using of these construction materials was considered important. Hence, the findings of this study are seen from the perspective of quantity surveyors, construction managers and project managers in Nigeria and South Africa. Nigeria was selected as a result of its high population and the increased pressure on limited available earth resources (Ogundare and Ogunbodede, 2014), which has necessitated the need for a more sustainable environment. South Africa on the other hand, is seen as one of the striving African countries with more advancement and an enabling environment for innovative ideas (Dall’Omo, 2017). However, the country, just like other developing countries is still struggling to fully embrace the concept of SC in its construction industry. Construction in South Africa is characterised by poor project performance (Emuze, 2011) amongst other issues. Therefore, understanding the challenges of SC in these two countries with distinct characteristics can give a reasonable insight to happenings in other developing countries, particularly in Africa where construction processes are almost similar. Subsequent parts of this paper include a review of the literature regarding the challenges of SC, the methodology adopted for the study, the findings and discussion and the conclusion made thereof.

**Literature review**

The delivery of SC projects has met with several obstructions. William and Dair (2012) observed a lack of knowledge, information and understanding as a major problem to the delivery of sustainable structures. In addition, Opoku and Ahmed (2015) stated that public awareness and proper knowledge and understanding of sustainability are essential to the
successful promotion of SC practices. Aghimien et al. (2018a), Aigbavboa et al. (2017), Alabi (2012), Al-Sanad (2015), Baron and Donath (2016) and Nguyen et al. (2017) all noted sustainability awareness and knowledge related factors as some of the major factors affecting SC in Nigeria, South Africa, Kuwait, Ethiopia and Vietnam. Thus, poor understanding of the concept of SC in its holistic form can be a major challenge towards achieving SC.

This poor understanding can lead to a misconception regarding the adoption of SC concepts leading to high investment cost. Although some studies have claimed that the initial cost of implementing SC is high (Darko and Lowe, 2016), incorporating life cycle costing during the assessment of the various costs and their implications will to a large extent show the beneficial attributes of SC on the long-term (Shi et al., 2013). Isa et al. (2013) in Malaysia and Zhang et al. (2011) in China identified the perceived high initial costs of SC as a major factor affecting the SC adoption. In agreement Ametepey et al. (2015) and Halkinen and Belloni (2011) pointed out that there is a fear of higher investment costs for SC as compared to traditional building. This tends to deter the use of SC materials. Aigbavboa et al. (2017) and Lowe and Zhou (2003) attributed this problem to the assumption made by construction participants, particularly estimators with regards to the cost of introducing SC concept and materials. This assumption is made without a thorough evaluation of the actual cost and whole-life cycle cost of adopting this concept. Aigbavboa et al. (2017) further described this assumption as a “lazy view” of construction participants, and this according to Lowe and Zhou (2003) is a serious problem to the proper adoption of SC in most countries around the world.

Djokoto et al. (2014) observed that the cultural background within an environment can play an active role in the adoption of new ideas. In most cases, moving from the known to the unknown might prove difficult, hence, stagnation in the existing situation may be observed as the existing state might not favour development. Aghimien et al. (2018a) submitted that if SC is to be achieved within the Nigerian construction industry, the industry needs to jettison the traditional method of construction for a more innovative SC approach. According to Ametepey et al. (2015), the construction industry has operated in a particular style for a long period of time and this has made the industry rigid in terms of adopting changes especially with respect to construction practices and use of building materials.

Ogunkah and Yang (2013) attributed this resistance to change to the preference of construction clients. This is understandable as in most cases the activities of the construction industry are determined by the client. Mousa (2015) noted that the client-driven nature of the construction industry leaves little room for the use of sustainable products. This is because clients with insufficient knowledge prematurely eliminate any alternative that is not commonly used. A client will most likely stick to what he already knows instead of taking chances on materials he is unfamiliar with. It is based on this challenge that Oke et al. (2019) submitted that if SC is to improve in developing countries through the use of sustainable practices, then clients need to demand it. This challenge can be linked to the challenge of inadequate exemplar “demonstration project” as observed by Ametepey et al. (2015). When there is little or no existing SC project to serve as a guide, there is bound to be problems in constructing one. The need for adequate information on past SC projects is crucial to create a roadmap in achieving SC in subsequent ones. Azman et al. (2013), Hatamleh et al. (2018) and Kissi et al. (2018) all noted that limited access to historical data has been a key limiting factor of SC in most developing countries.

Aside from client’s preference and demand it is believed that proper adoption of SC material for construction cannot be fully achieved without top management support
(Abisuga and Oyekanmi, 2014; Ametepey et al., 2015). The issue of the absence of building codes and regulations hindering the adoption of SC was also mentioned by Oke et al. (2019) and Hakkinen and Belloni (2011). Powmya and Abidin (2014) further stated that government plays a key role in the enforcement of regulation, revision of existing legislation and policies, the introduction of building codes, incentives and other fiscal instruments to spear-head SC adoption. Oke et al. (2019) also noted that if SC is to be achieved, legislation must be put in place to promote it. The study further concluded that the existence of building regulations to support SC and measures to enforce them are key drivers of SC in developing countries such as Zambia. It is based on this wealth of knowledge that the different challenges of SC as seen in Table I were assessed in this study.

<table>
<thead>
<tr>
<th>Code</th>
<th>Challenges</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH1</td>
<td>Resistance to change within the construction industry</td>
<td>Aghimien et al. (2018a), Kissi et al. (2018) and Osaily (2010)</td>
</tr>
<tr>
<td>CH3</td>
<td>Clients preference</td>
<td>Ogunkah and Yang (2013) and Mousa (2015)</td>
</tr>
<tr>
<td>CH4</td>
<td>Inadequate knowledge and understanding of the concept of sustainability</td>
<td>Aghimien et al. (2018a), Abikiyi et al. (2009), Abidin et al. (2003), Aigbavbo et al. (2017), Djokoto et al. (2014) and Kissi et al. (2018)</td>
</tr>
<tr>
<td>CH5</td>
<td>Limited access to relevant information and historical data</td>
<td>Hatamleh et al. (2018)</td>
</tr>
<tr>
<td>CH7</td>
<td>Lack of expert opinions on SC</td>
<td>Aigbavbo et al. (2017), Odusami and Onukwubu (2008) and Ogunkah and Yang (2013)</td>
</tr>
<tr>
<td>CH8</td>
<td>Client worries in profitability</td>
<td>Ametepey et al. (2015)</td>
</tr>
<tr>
<td>CH9</td>
<td>Inadequate exemplar “demonstration project”</td>
<td>Ametepey et al. (2015)</td>
</tr>
<tr>
<td>CH10</td>
<td>Inadequate technology and technological process</td>
<td>Kibert (2013)</td>
</tr>
<tr>
<td>CH11</td>
<td>Interest, direction and commitment of top management</td>
<td>Abisuga and Oyekanmi (2014) and Ametepey et al. (2015)</td>
</tr>
<tr>
<td>CH12</td>
<td>Unstable prices of construction</td>
<td>Azhar et al. (2008)</td>
</tr>
<tr>
<td>CH13</td>
<td>Unreliability of Suppliers</td>
<td>Ogunkah and Yang (2013)</td>
</tr>
<tr>
<td>CH14</td>
<td>Limited availability of sustainable materials in market/market conditions</td>
<td>Abidin et al. (2003), Baron and Donath (2016), Odusami and Onukwubu (2008) and Ogunkah and Yang (2013)</td>
</tr>
<tr>
<td>CH15</td>
<td>Low demand level for sustainable products</td>
<td>Djokoto et al. (2014) and Opoku and Ahmed (2015) and Williams and Dair (2007)</td>
</tr>
<tr>
<td>CH16</td>
<td>Inadequate sustainability measurement tools</td>
<td>Osaily (2010) and Parkin et al. (2003)</td>
</tr>
<tr>
<td>CH17</td>
<td>Perception that SC materials are of low status</td>
<td>Kissi et al. (2018)</td>
</tr>
<tr>
<td>CH19</td>
<td>Inadequate building codes and regulations on sustainability</td>
<td>Abidin et al. (2003) and Hakkinen and Belloni (2011)</td>
</tr>
<tr>
<td>CH20</td>
<td>Level of integration of life cycle cost</td>
<td>Ametepey et al. (2015) and Shi et al. (2013)</td>
</tr>
</tbody>
</table>

Table I. List of challenges of SC
Research methodology

This study set out to assess the challenges facing SC in two developing African countries; Nigeria and South Africa. The study followed the conventional research approach adopted by Choi (2012). This involves first understanding the key area of the study and conducting an in-depth review of the existing literature in line with the study’s objectives. After the review, a survey approach was adopted with a questionnaire as the research instrument. Data gathered were analysed, inferences were drawn from the results and conclusions were made thereof. The choice of a survey approach with questionnaire used in gathering quantitative data is premised on the fact that the study solicited responses from professionals across two countries. Using a qualitative approach through an interview or other approaches would have been time-consuming and almost practically impossible to achieve. The questionnaire survey was deemed suitable because of its ease of usage and its ability to cover a wider range of audience within a short period of time (Tan, 2011). Moreover, Ackroyd and Hughes (1981) have earlier stated that the questionnaire has the ability to achieve quantifiability and objectiveness in research. According to Blaxter et al. (2001), the questionnaire is among the most widely used social research techniques, hence, its adoption for this study.

The questionnaire used was close-ended, designed in three sections, with the first geared towards gathering information on the background of the respondents. The second harnessed information on the awareness and usage of SC materials while the third harnessed information in the challenges of SC. Respondents were provided with a total of 20 variables to rate based on their level of severity using a five-point Likert scale, with five being very severe, four severe, three moderate, two less severe and not severe. A similar approach was adopted in studies on green building procurement, promotion of green building and SC practices (Aghimien et al., 2018b; Chan et al., 2017; Wong et al., 2016). The questionnaire was distributed among quantity surveyors, construction managers and project managers because of their role in the estimation and use of construction materials and the management of construction projects. As the study cut across two countries, an electronic questionnaire was adopted for easy sending and collection of feedbacks. Professionals were identified from the different professional database and were sampled conveniently based on their willingness to participate in the study. Also, a snowball approach was adopted to further broaden the reach of the study. This became necessary due to the limitation encountered while trying to reach some of these professionals as some emails were not available. The snowball approach can be useful when there is a need to increase the sample size (Atkinson and Flint, 2001) as in the case of this present study. This approach is similar to that adopted in Chan et al. (2017) and Rahman (2014). Following the approach adopted, the exact number of distribution cannot be determined, thus, making the calculation of a total response rate impossible. However, a total of 122 responses were collected and this was considered adequate for the study following the submission of Cheng and Li (2002) that there is always difficulty eliciting responses from international respondents.

In analysing the data gathered, Choi (2012)’s five levels of data analyses and Chan et al. (2017) and Wong et al. (2016)’s six levels were further modified into four distinct levels as seen in Figure 1. The data gathered were analysed by first determining their normality, using Shapiro-Wilk test and the reliability of the research instrument through the use of Cronbach’s alpha test. Cronbach’s alpha gives an alpha value between 0 and 1, and the higher the value, the more reliable the questionnaire (Moser and Kalton, 1999). An alpha value of 0.945 was achieved for the 20 assessed challenges and this shows that the instrument is reliable. The structure validity of the measurement scale adopted was also
tested using Kaiser–Meyer–Olkin (KMO) and Bartlett test analyses. Result gave a KMO value of 0.917 while the Bartlett test gave an approximate chi-square of 1,501.75 at a degree of freedom of 190 and a significant $p$-value of 0.000. This result implies that the scale adopted is valid for what it was designed to assess as the ideal range for a KMO value is 0.60 and above and $p$-value of less than 0.05 for Bartlett test (Tabachnick and Fidell, 2007). The second stage was the use of mean item score (MIS) to rank the identified challenges based on their level of significance in both countries. This was used in conjunction with the derived standard deviation (SD) for the challenges. These challenges were ranked from the highest MIS to the lowest. However, where two variables have the same MIS the variable with the lowest SD is ranked first as suggested by Field (2005). Gap analysis was then used to determine the mean difference of these challenges. A similar approach was adopted by Oke et al. (2018) in analysing the difference in the mean value of foreign and indigenous contractors’ response in Nigeria. Likewise, Mann–Whitney U-test, which is a non-parametric test was adopted in testing the significant difference in responses from professionals from the two countries.

**Findings and discussion**

**Background information of respondents**

The analysis revealed that more responses were gotten from Nigeria (57 per cent) with 43 per cent coming from South Africa. In terms of profession, 69 per cent were quantity surveyors, 18 per cent were construction managers while 13 per cent were project managers. Furthermore, 71 per cent of the respondents works in private organisations while 29 per cent are working within the public sector. In terms of years of experience, 48 per cent of the respondents have 5 years and below working experience, while the remaining 52 per cent have over 5 years working experience in the built environment. On average, the respondents have 7.5 years of working experience, which is considerably high and makes their response more credible as it was based on their experience.

In ascertaining the respondents’ knowledge of SC, their awareness and involvement in using SC materials were assessed. The result in Table II revealed that majority of the construction professionals from both countries (Nigeria = 67; South Africa = 47) indicated
that they are aware that there are alternative sustainable building materials as against the traditional materials being used on a daily basis. Only three respondents from Nigeria and five from South Africa stated lack of awareness as regards the existence of these materials. This result implies that there exists considerable awareness as regards SC materials among the assessed professionals in both countries. This high awareness level can be attributed to the high years of working experience of these professionals within the construction industry. As overtime SC has become a popular concept within the built environment, the level of awareness of professionals as regards the concept is likely to increase with the years spent within the industry. However, the story is not the same when it comes to the level of usage of SC materials on construction projects, as more respondents from Nigeria (61) claim to have participated in the usage than those from South Africa (27). On a unified view, out of the 114 professionals that are aware of the availability of SC materials for building construction, 88 (77 per cent) have been involved in the usage and 26 (23 per cent) have not. Although the level of involvement is high, 23 per cent shows that there is still some level of non-usage of SC materials for construction.

In terms of the building elements where SC materials are mostly used, eight building elements were presented to the respondents and they were given the opportunity to pick more than one option as it applies to them. The result in Figure 3 shows that surface finishing for wall, floor and ceiling had the highest frequency (35) in Nigeria and this is followed by masonry construction with a frequency of 30. However, the reverse was the case in South Africa as masonry had the highest frequency of 16 followed by surface finishing for wall, floor and ceiling with a frequency of 15. This result can be attributed to the high use of compressed earth bricks (which is considered to be a sustainable material for masonry construction due to its less use of cement) in South Africa, unlike Nigeria where its usage is just gradually gaining popularity (Aghimien et al., 2016). On the overall, it is evident that surface finishing for wall, floor and ceiling, and masonry construction were the most common building elements wherein SC materials are being used. For both countries, SC materials for mechanical works in buildings seem not to be a common practice as it has the lowest frequency of 19 on the overall (Table III).

### Challenges of sustainable construction

**Challenges of sustainable construction in Nigeria**

In determining the challenges facing SC in Nigeria, first, the normality of the data gathered were tested. The premise for conducting the normality test was to determine whether the data is parametric or non-parametric to ascertain the type of analysis to be conducted. Ghasemi and Zahediasl (2012) suggested that the Shapiro-Wilk normality test is most suitable for assessing the normality of data gathered from a sample size of less than 2,000. Using the Shapiro-Wilk test the result in Table IV shows that the significant value of all the 20 assessed challenges is 0.000, which is less than the 0.05 required criteria for normality. This implies that the data gathered is non-parametric in nature, hence, only non-parametric analysis can be conducted. The result in Table IV also revealed that out of the 20 assessed

<table>
<thead>
<tr>
<th>Country</th>
<th>Awareness Yes</th>
<th>Awareness No</th>
<th>Total</th>
<th>Usage Yes</th>
<th>Usage No</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nigeria</td>
<td>67</td>
<td>3</td>
<td>70</td>
<td>61</td>
<td>6</td>
<td>67</td>
</tr>
<tr>
<td>South Africa</td>
<td>47</td>
<td>5</td>
<td>52</td>
<td>27</td>
<td>20</td>
<td>47</td>
</tr>
<tr>
<td>Total</td>
<td>114</td>
<td>8</td>
<td>122</td>
<td>88</td>
<td>26</td>
<td>114</td>
</tr>
</tbody>
</table>
variables, 19 had a mean value of the above average of 3.0. This means that respondents believe that these 19 variables significantly affect the SC in the country. Furthermore, result revealed that the most significant challenges are resistance to change within the construction industry (CH1) \((MIS = 3.43, \text{SD} = 1.162)\), clients fear of SC materials leading to high investment cost (CH2) \((MIS = 3.43, \text{SD} = 1.234)\), inadequate awareness and knowledge of the concept of sustainability (CH4) \((MIS = 3.40, \text{SD} = 1.224)\), inadequate technology and technological process (CH10) \((MIS = 3.37, \text{SD} = 1.092)\), inadequate government policies/support (CH6) \((MIS = 3.36, \text{SD} = 1.143)\), inadequate exemplar demonstration project (CH9) \((MIS = 3.33, \text{SD} = 1.003)\), clients preference (CH3) \((MIS = 3.33, \text{SD} = 1.126)\), unstable prices of SC materials (CH12) \((MIS = 3.33, \text{SD} = 1.139)\), and limited access to relevant information and historical data (CH5) \((MIS = 3.30, \text{SD} = 1.081)\). These challenges are ranked by their mean item score (MIS) and standard deviation (SD) in Table IV.

### Table III.
Elements were SC materials are most priced

<table>
<thead>
<tr>
<th>Building elements</th>
<th>Frequency</th>
<th>Rank</th>
<th>Frequency</th>
<th>Rank</th>
<th>Frequency</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface finishing (floor, walls and ceiling)</td>
<td>35</td>
<td>1</td>
<td>15</td>
<td>2</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>Masonry</td>
<td>30</td>
<td>2</td>
<td>16</td>
<td>1</td>
<td>46</td>
<td>2</td>
</tr>
<tr>
<td>Foundation</td>
<td>25</td>
<td>3</td>
<td>11</td>
<td>4</td>
<td>36</td>
<td>3</td>
</tr>
<tr>
<td>Roofing</td>
<td>24</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>34</td>
<td>4</td>
</tr>
<tr>
<td>Windows and doors</td>
<td>25</td>
<td>3</td>
<td>7</td>
<td>6</td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td>Electrical works</td>
<td>18</td>
<td>7</td>
<td>14</td>
<td>3</td>
<td>32</td>
<td>6</td>
</tr>
<tr>
<td>Structural framing</td>
<td>20</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>25</td>
<td>7</td>
</tr>
<tr>
<td>Mechanical works</td>
<td>15</td>
<td>8</td>
<td>4</td>
<td>8</td>
<td>19</td>
<td>8</td>
</tr>
</tbody>
</table>

### Table IV.
Challenges of SC in Nigeria

<table>
<thead>
<tr>
<th>Challenges</th>
<th>MIS</th>
<th>SD</th>
<th>Rank</th>
<th>Shapiro-Wilk Statistic</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance to change within the construction industry (CH1)</td>
<td>3.43</td>
<td>1.162</td>
<td>1</td>
<td>0.884</td>
<td>0.000</td>
</tr>
<tr>
<td>Clients fear of SC materials leading to high investment cost (CH2)</td>
<td>3.43</td>
<td>1.234</td>
<td>2</td>
<td>0.895</td>
<td>0.000</td>
</tr>
<tr>
<td>Inadequate awareness and knowledge of the concept of sustainability (CH4)</td>
<td>3.40</td>
<td>1.224</td>
<td>3</td>
<td>0.894</td>
<td>0.000</td>
</tr>
<tr>
<td>Inadequate technology and technological process (CH10)</td>
<td>3.37</td>
<td>1.092</td>
<td>4</td>
<td>0.881</td>
<td>0.000</td>
</tr>
<tr>
<td>Inadequate government policies/support (CH6)</td>
<td>3.36</td>
<td>1.143</td>
<td>5</td>
<td>0.886</td>
<td>0.000</td>
</tr>
<tr>
<td>Inadequate exemplar demonstration project (CH9)</td>
<td>3.33</td>
<td>1.003</td>
<td>6</td>
<td>0.905</td>
<td>0.000</td>
</tr>
<tr>
<td>Clients preference (CH3)</td>
<td>3.33</td>
<td>1.126</td>
<td>7</td>
<td>0.911</td>
<td>0.000</td>
</tr>
<tr>
<td>Unstable prices of SC materials (CH12)</td>
<td>3.33</td>
<td>1.139</td>
<td>8</td>
<td>0.903</td>
<td>0.000</td>
</tr>
<tr>
<td>Limited access to relevant information and historical data (CH5)</td>
<td>3.30</td>
<td>1.081</td>
<td>9</td>
<td>0.875</td>
<td>0.000</td>
</tr>
<tr>
<td>Inadequate sustainability measurement tools (CH16)</td>
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<td>10</td>
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<td>11</td>
<td>0.896</td>
<td>0.000</td>
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<td>1.173</td>
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<td>0.854</td>
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<td>Client worries on profitability (CH8)</td>
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<td>15</td>
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<td>0.000</td>
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<tr>
<td>Unreliability of Suppliers (CH13)</td>
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<td>1.020</td>
<td>16</td>
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<td>1.135</td>
<td>17</td>
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<td>19</td>
<td>0.894</td>
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<tr>
<td>Method of selecting SC material (CH18)</td>
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<td>0.909</td>
<td>20</td>
<td>0.893</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**Notes:** MIS = mean item score; SD = standard deviation
Challenges of sustainable construction in South Africa

In analysing data gathered from South Africa, the Shapiro-Wilk test for normality revealed that the significant value of all the 20 assessed challenges is well below 0.05 required criteria for normality (Table V). This implies that the data gathered is non-parametric in nature. The result in Table V also revealed that all the assessed variables gave a mean value of the above average of 3.0, which implies that respondents believe that all the 20 variables are significant. The most significant challenges are resistance to change (CH1) \((MIS = 3.69, SD = 1.197)\), clients’ fear of SC materials leading to high investment cost (CH2) \((MIS = 3.65, SD = 1.046)\), client’s preference (CH3) \((MIS = 3.56, SD = 1.110)\) and limited access to relevant information and historical data (CH5) \((MIS = 3.54, SD = 1.196)\). The least and non-severe challenge is the method of selecting SC material (CH18) with an MIS of 2.99 and an SD of 0.909.

**Table V. Challenges of SC in South Africa**

| Challenges                                                                 | MIS   | SD    | Rank | Shapiro-Wilk Statistic | Sig. |
|.................................................................................................................. |-------|-------|------|------------------------|------|
| Resistance to change within the construction industry (CH1)               | 3.69  | 1.197 | 1    | 0.871                  | 0.000|
| Clients fear of SC materials leading to high investment cost (CH2)        | 3.65  | 1.046 | 2    | 0.869                  | 0.000|
| Clients preference (CH3)                                                  | 3.56  | 1.110 | 3    | 0.899                  | 0.000|
| Limited access to relevant information and historical data (CH5)          | 3.54  | 1.196 | 4    | 0.869                  | 0.000|
| Client worries on profitability (CH8)                                     | 3.48  | 0.980 | 5    | 0.902                  | 0.000|
| Lack of expert opinions on sustainable construction (CH7)                 | 3.48  | 1.244 | 6    | 0.890                  | 0.000|
| Inadequate awareness and knowledge of the concept of sustainability (CH4) | 3.46  | 1.212 | 7    | 0.895                  | 0.000|
| Inadequate government policies/support (CH6)                              | 3.40  | 1.257 | 8    | 0.890                  | 0.000|
| Unreliability of suppliers (CH13)                                         | 3.37  | 1.103 | 9    | 0.896                  | 0.000|
| Interest, direction and commitment of top management (CH11)               | 3.33  | 1.133 | 10   | 0.904                  | 0.001|
| Inadequate exemplar demonstration project (CH9)                           | 3.25  | 1.235 | 11   | 0.893                  | 0.000|
| Method of selecting SC material (CH18)                                     | 3.23  | 0.942 | 12   | 0.868                  | 0.000|
| Perception that SC materials are of low status (CH17)                     | 3.21  | 1.109 | 13   | 0.912                  | 0.001|
| Limited availability of sustainable materials in market (CH14)            | 3.17  | 1.150 | 14   | 0.917                  | 0.001|
| Inadequate technology and technological process (CH19)                    | 3.10  | 1.272 | 15   | 0.902                  | 0.000|
| Unstable prices of SC materials (CH12)                                    | 3.15  | 1.195 | 16   | 0.916                  | 0.001|
| Level of integration of life cycle cost (CH20)                            | 3.13  | 1.103 | 17   | 0.917                  | 0.001|
| Low demand level for sustainable products (15)                            | 3.12  | 1.149 | 18   | 0.907                  | 0.001|
| Inadequate building codes and regulations on sustainability (CH19)        | 3.10  | 1.176 | 19   | 0.918                  | 0.002|
| Inadequate sustainability measurement tools (CH16)                        | 3.02  | 1.111 | 20   | 0.914                  | 0.001|

**Notes:** MIS = mean item score; SD = standard deviation
information and historical data (CH5) \((MIS = 3.54, SD = 1.196)\). The least ranked challenge is inadequate sustainability measurement tools (CH16) with an MIS of 3.02 and an SD of 1.111.

**Challenges of sustainable construction in Nigeria and South Africa**

The result in Table VI shows the mean value of the assessed challenges, their rank order, the gap between the mean of the two countries, the Z-value and significant \(p\)-value derived from Mann–Whitney U-test conducted. Looking at the result from both countries, it is evident that respondents from both countries consider the resistance to change within the construction industry (CH1) and client’s fear of an increase in investment cost (CH2), as a crucial problem facing SC. However, some disparity exists in the ranking of most of the other variables. It is also important to note that among the top challenges in the two countries, inadequate technology and technological process (CH10) was considered a crucial issue for professionals in Nigeria, but this does not appear among the top factors rated by those in South Africa. On the other hand, client preference (CH3) was rated among the top challenges by respondents in South Africa but was not in Nigeria (Figure 2).

Mean gap analysis conducted to show the difference in the mean value of the challenges as rated by both countries shows that the gap in both countries is somewhat low with the highest being 0.312 and the lowest being 0.05. The greatest mean gap exists in client worries on profitability (CH8), resistance to change (CH1), method of selecting SC materials (CH18) and unreliability of suppliers (CH13) with a mean gap of 0.31, 0.26, 0.25 and 0.24, respectively. It is worthy of note to state that out of these four challenges only resistance to

<table>
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<tr>
<th>Code</th>
<th>Nigeria MIS</th>
<th>Rank</th>
<th>South Africa MIS</th>
<th>Rank</th>
<th>Gap</th>
<th>Overall MIS</th>
<th>Rank</th>
<th>Mann–Whitney Z-value</th>
<th>Sig.</th>
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Overall Mann–Whitney U-test 160.500
Wilcoxon W 370.500
Z -1.070
Asymp. significance (two-tailed) 0.285

**Notes:** MIS = mean item score; and Sig. = significant \(p\)-value
change (CH1) had the same rank for both countries. The other three, however, had a significant disparity in their ranking. While client worries in profitability was ranked as the 15 significant challenge in Nigeria, it ranked 5th in South Africa. Similarly, the method of selecting SC materials is considered as the least significant challenge in Nigeria while in South Africa it is considered as the 12th. The unreliability of suppliers is ranked as 13th in Nigeria and 9th in South Africa. Judging from this result, it can be seen that while professionals in South Africa considered these three challenges to be significant, those in Nigeria believe there are other challenges that are far more significant than these three. This disparity may be attributed to the type of clients and the nature of their business orientation, the method of choosing materials to use for construction and the nature of suppliers within both countries of study.

On a more unified view, the result revealed that the overall mean value for the 20 assessed challenges is above the average of 3.0 (Figure 3). This implies that all assessed challenges have the ability to affect SC in both countries. Chief of these challenges are resistance to change (CH1), clients fear of SC materials leading to high investment cost (CH2), client’s preference (CH3), inadequate knowledge and understanding of the concept of sustainability (CH4), limited access to relevant information and historical data (CH5), inadequate government policies/support (CH6) and lack of expert opinions on SC (CH7) with a mean value of 3.54, 3.52, 3.43, 3.43, 3.40, 3.36 and 3.35, respectively. The least challenges are the method of selecting SC materials (CH18), inadequate building codes and regulations on sustainability (CH19) and level of integration of life-cycle cost (CH20) with a mean value of 3.09, 3.07 and 3.05, respectively. Although they are ranked as the least, their mean values are above the average of 3.0, which means that to some extent these challenges still affect SC in both countries, though on a minimal scale when compared to the rest challenges.

**Hypothesis testing**

Considering the fact that both assessed countries are developing countries in Africa, it was assumed that some of the significant challenges facing SC in both countries might be the same while some may differ, hence a hypothesis was set in this regards. The null hypothesis (H0) set was that there is no significant difference in the opinion of construction professionals in Nigeria and South Africa in terms of the challenges of SC. The alternate
hypothesis was that there is a significant difference in the opinion of construction professionals in Nigeria and South Africa in terms of the challenges of SC. Following the result of the normality test, which shows that the assessed variables are non-parametric in nature, a non-parametric test was deemed necessary in order to test the set hypothesis. Mann–Whitney U-test, which is a non-parametric alternative of t-test in assessing independent samples was adopted. Unlike t-test, which compares the mean value of two groups, Mann–Whitney U-test compares medians of the groups and converts the scores on the continuous variable to ranks, and determines the significant difference between both groups (Pallant, 2005). This test gives a Z-value and a significant p-value. When the derived p-value is lower than the predetermined significance value of 0.05, it means that there is a significant difference in the median value of the two groups (Choi, 2012; Pallant, 2005). In the case of this current study, this implies that there is a significant difference in the view of respondents from both countries. However, the reverse is the case if the derived p-value is greater than the predetermined significance value of 0.05. This means that there is no significant difference in the view of respondents from both countries. Wong et al. (2016) adopted this approach in determining individual critical factors that contribute to the differences between groups of respondents in their study on green building procurement. Looking at the last column in Table VI, Mann–Whitney U-test shows that all the assessed challenges have a significant p-value of above the predetermined value of 0.05. This result implies that despite the disparity in the ranking of some of the assessed challenges by respondents from both countries, there is no statistically significant difference in the professionals’ view as regards each of the individual assessed challenges. Using a unified view in testing the stated hypothesis, the result revealed a Z-value of –1.070 and a significant p-value of 0.285. This means that there is no statistically significant difference in the view of the professionals from both countries as regards the challenges facing SC in Nigeria and South Africa. Thus, the H0 is accepted and the alternate hypothesis rejected. The implication of this finding is that the professionals from both countries see the challenges facing SC in both developing countries from the same viewpoint and this gives more credibility to the conclusion drawn from the findings.
Discussion of findings

Findings of this study revealed that there is considerable awareness as regards the SC among quantity surveyors, construction managers and project managers in Nigeria and South Africa. This result implies that there is an increase in SC awareness in these countries when compared to the earlier submissions of Alabi (2012) and Aigbavboa et al. (2017). However, despite this increase in awareness, more of these professionals have been involved in the use of SC materials in Nigeria than in South Africa. This difference in result might be associated with the difference in the number of samples collected from both countries, with more responses gotten from Nigeria. On a unified view, there is a considerable high level of involvement in the use of SC materials by professionals in both countries. In terms of the building elements where SC materials are mostly used, surface finishing for the wall, floor and ceiling, and masonry construction were the most common while using its usage for mechanical works in buildings seem not to be a common practice.

In Nigeria, the most significant challenges of SC are resistance to change, client’s fear of SC materials leading to high investment cost, inadequate knowledge and understanding of the concept of sustainability, inadequate technology and technological process and inadequate government policies/support. However, in South Africa, the most significant challenges are resistance to change, clients’ fear of SC materials leading to high investment cost, clients’ preference and limited access to relevant information and historical data. Among these top challenges, inadequate technology and the technological process was deemed significant in Nigeria, but not in South Africa, whereas client preference was rated among the top challenges in South Africa but was not in Nigeria. This disparity can be attributed to the technological advancement South Africa has attained over time when compared to other African countries (Nigeria inclusive). Thus, the issue relating to technology and technological processes might not be a huge problem in the country, unlike Nigeria where technological advancement is still an issue (Mbamali and Okotie, 2012). A study conducted by Siemens in ascertaining the digital technology readiness of some African countries shows that South Africa ranked the highest over Nigeria, Kenya and Ethiopia (Dall’Omo, 2017). The finding of the study is a pointer to the fact that South Africa has the enabling environment for technological advancement than other African countries.

In general, findings revealed that there is no statistically significant difference in the view of the professionals from Nigeria and South Africa as regards the challenges facing SC in developing countries. The significant challenges identified are resistance to change within the construction industry, clients fear of SC materials leading to high investment cost, client’s preference, inadequate knowledge and understanding of the concept of sustainability, limited access to relevant information and historical data, inadequate government policies/support and lack of expert opinions on SC. It has been established that there is a significant amount of resistance to change within the construction industry. Embracing innovation in terms of process and materials is an issue affecting the industries development. Similarly, this issue affects the use of SC materials as both clients and professionals tend to stick to what they know rather than what is new. Therefore, if any improvement is going to be attained in terms of delivering SC, a change from the norm to adopting new ideas is necessary. This finding is in line with the submissions of Ametepey et al. (2015) and Osaily (2010), which stated that resistance to change is a crucial issue facing SC in Ghana and Palestine.

It is believed that proper life-cycle costing will give a vivid view of the overall cost-benefit of SC (Shi et al., 2013). This is needed to alienate clients fear with regards to SC materials leading to high investment cost. Kissi et al. (2018) also submitted that economic issue such as fear of high investment cost is a major factor affecting SC in Ghana. A similar
observation was made by Isa et al. (2013) in Malaysia and Zhang et al. (2011) in China. Therefore, proper enlightening of construction clients as regards the inherent benefit of adopting SC is necessary. Through this enlightenment of clients, their preference knowledge and understanding of the concept of sustainability can also change as these two factors are among the key challenges affecting SC in the assessed countries. It is only by knowing and understanding the inherent benefits of the adoption of SC that their preference can change from the traditional materials to more sustainable ones. Aside, enlightening the clients, construction practitioners also need to increase their understanding of SC. By so doing, more expert opinion can be generated within the industry to guide and direct the attainment of sustainability in project delivery. This finding is in tandem with the submissions of Al-Sanad (2015), Mousa (2015), Nguyen et al. (2017), Ogunkah and Yang (2013), Opoku and Ahmed (2015) and William and Dair (2012) that client’s preference and lack of knowledge, information and understanding are some of the major barriers to achieving sustainable structures.

The findings of this study also show that limited access to relevant information and historical data is a key challenge facing SC. This finding is in tandem with the submissions of Azman et al. (2013), Hatamleh et al. (2018) and Kissi et al. (2018), which reveal information issue as critical challenges in Malaysia, Jordan and Ghana. The low level of adoption of SC in most developing countries is bound to affect the availability of historical data that will serve as a reference or guide for SC. Aside issue of information, inadequate government policies and support has proven to be another challenge. If the adoption of SC is to increase, then government support through policy creation and enforcement is crucial (Oke et al., 2019). Powmya and Abidin (2014) have earlier stated that government plays a key role in the creation and enforcement of policies that will spear-head SC adoption. This finding further corroborates the submission of Ametepey et al. (2015) and Osaily (2010), which shows that a lack of government support and policies are affecting SC in Ghana and Palestine.

Conclusion and recommendations
Based on the findings of this study, it is, therefore, concluded that there is a considerable level of awareness and usage as regards the SC materials in Nigeria and South Africa. The building elements where SC materials are most used are surface finishing and masonry construction. The implication of this finding is that while awareness is increasing in terms of SC materials, the usage of these materials is yet to be holistic in the delivery of building projects. Therefore, there is the need for further enlightening of construction participants (clients inclusive) on the need to adopt SC materials in building element such as mechanical works wherein SC materials are rarely used.

Professionals in Nigeria and South Africa have no statistically significant difference in their view as regards the most significant challenges of SC. The most significant challenges identified are resistance to change, clients fear of SC materials leading to high investment cost, client’s preference, inadequate knowledge and understanding of the concept of sustainability, limited access to relevant information and historical data, inadequate government policies/support and lack of expert opinions on SC. This result implies that for SC to improve, then a change from the norm to adopting new ideas is necessary. In addition, proper enlightening of construction clients and professionals in terms of SC is needed to alienate the client’s fear of an increase in investment cost and create a proper understanding of its inherent benefits. Also, this will help change their preference for traditional construction materials to the adoption of more sustainable ones. In addition, it will also help increase professionals knowledge and understanding of the concept of SC.
Experts in SC are lacking within the construction industry of most developing countries, hence, the absence of their opinions is affecting the embrace of SC. This situation calls for the need for experts on SC in the industry. This can be achieved through an increase in the education and training of construction professionals on SC principles and concepts. An increase in the teaching of sustainability concept in institutes of higher learning is important so as to prepare construction graduates as experts in SC. Also, respective professional bodies can assist by conducting training for their member in areas of SC. It has been revealed that poor information system is affecting SC, as in most cases information on projects is not available or properly stored for easy retrieval and use for subsequent projects. Therefore, there is a need for proper documentation of information on SC projects being conducted to have a means of reference when handling new projects. Finally, the government needs to be actively involved in promoting SC through the creation of policies and the provision of means of enforcing them. In addition, the government can support SC through the review and enforcement of legislation and policies and in the introduction of building codes, incentives and other fiscal instruments necessary for SC adoption.

The findings of this study contribute to the body of knowledge as it shows the awareness and involvement of construction professionals in the use of SC materials, the different building elements, wherein, SC materials are mostly used, and the challenges facing SC in these developing countries. Its uniqueness lies in the assessment of these challenges from two developing countries and its recommendation can to a large extent promote SC in these countries and other developing countries especially in Africa where the construction processes and conditions are similar. Although this study contributes significantly to the body of knowledge, its findings are limited by geographical boundaries. The construction process and orientation in some other developing countries might differ from what is obtainable in the two assessed countries and this can significantly affect the adoption and implementation of SC. Therefore, further studies on the challenges of SC can be extended to other developing countries where such studies have not been carried out. Similarly, a wider range of construction stakeholders can be assessed to get a much wider view of the topic.

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Spatial variability modeling and reliability analysis of flexible pavement through mechanistic–empirical model

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Abstract
Purpose – The present study aims to demonstrate the performance assessment of flexible pavement structure in probabilistic framework with due consideration of spatial variability modeling of input parameter.

Design/methodology/approach – The analysis incorporates mechanistic–empirical approach in which numerical analysis with spatial variability modeling of input parameters, Monte Carlo simulations (MCS) and First Order Reliability Method (FORM) are combined together for the reliability analysis of the flexible pavement. Random field concept along with Cholesky decomposition technique is used for the spatial variability modeling of the input parameter and implemented in commercially available finite difference code FLAC for the numerical analysis of pavement structure.

Findings – Results of the reliability analysis, with spatial variability modeling of input parameter, are compared with the corresponding results obtained without considering spatial variability of parameters. Analyzing a particular three-layered flexible pavement structure, it is demonstrated that spatial variability modeling of input parameter provides more realistic treatment to property variations in space and influences the response of the pavement structure, as well as its performance assessment.

Originality/value – Research is based on reliability analysis approach, which can also be used in decision-making for quality control and flexible pavement design in a given environment of uncertainty and extent of spatially varying input parameters in a space.

Keywords Reliability analysis, Pavement design

Paper type Research paper

Introduction
Structural design of flexible pavement requires estimation of thickness of different layers resting on the subgrade soil – although geometrically simple, this is one of the most
daunting tasks to accomplish. Complexity in flexible pavement design gets enhanced by mix traffic condition with different axle configurations and loads on one hand and material behavior and pavement response under different environmental conditions on the other. During the 1920s, pavement sections were designed based on the subgrade shear strength. In 1929, California Highway Department proposed CBR (California bearing ratio) test that was related to the shear strength of the subgrade soil. Empirical pavement design methods based on CBR of subgrade were developed to provide the thickness of the pavement layer that can be safely supported by the subgrade with anticipated design traffic load throughout the life of the pavement. During the 1950s, the CBR method was the most popular and widely used for the design of flexible pavements and, later, it was suggested with modifications by USACE (US Army Corps of Engineers), HRB (Highway Research Board), Asphalt Institute and several other agencies throughout the world. In due course, with increased traffic loads and experience, performance parameters, such as riding quality and distress analysis, were given due consideration in pavement analysis and design to check the deterioration rate of pavements. On these lines of thoughts, AASHTO (during the 1960s) proposed empirical design guidelines based on serviceability index and, later, published an interim guide for the design of pavement structures. With extensive research, experimentation and consideration of new factors and variables affecting the design of pavements, AASHTO (1993) expanded the existing guidelines that took into consideration the reliability aspect, resilient modulus of soil support and flexible pavement layer coefficients, drainage, environment consideration, tied concrete shoulders or widened lane, sub-base erosion, life-cycle cost consideration, rehabilitation, etc. AASHTO (1993) is now one of the most widely accepted empirical design procedures for pavements.

It is well understood that empirical design guidelines are based on experimentations and experience and have their own limitations, as they are applicable under the condition, circumstances and situation in which they are developed. In view of that, researchers also adopted a mechanistic model for the analysis and design of pavements in which quantitative analysis of the pavement structures are undertaken by considering the elastic layer theory (Burmister, 1945). In recent years, Gholamali Shafabakhsh et al. (2018) used FEM-based Abacus software to study the pavement response, i.e. stress and deflection of a runway at different speeds. Such approaches provided a good option for the mechanistic analysis of pavements and reinforced the concept with time with the development of new materials. Recently, Senaratne et al. (2018) proposed a new construction material using steel fibers (SF) and recycled aggregates (RA) for concrete, and they reported that 30 per cent RA and 0.3 SF replacement volume content provided the optimum results in laboratory experimentations. Vaishali Sahu et al. (2017) suggested a new material for base course using lime sludge and fly ash after stabilization and adding ductility properties through synthetic fibers. These new road-construction materials developed for providing better riding quality and improved support to subgrade had their own failure mechanism and failure criteria, and it was well supported in the mechanistic analysis by easily adapting different constitutive models pertaining to the material used. For example, fatigue cracking and permanent deformation (rutting) in asphalt concrete could easily be considered in mechanistic approach. With extensive research and incorporation of these failure mechanisms in pavement analysis, design guidelines were provided by Asphalt Institute (1991). Purely mechanistic model is not yet developed because of difficulties in incorporating the realistic material behavior and environment conditions in the mechanical analysis, as it can be easily incorporated in empirical models. Hence, mechanistic methods necessitated combination of elastic analysis of pavement layers for calculation of strains, stress or deflections at critical locations and empirical models to predict the number of load repetitions required to cause failure.
Such mechanistic–empirical hybrid models are preferred over completely empirical or fully mechanistic approaches to fill the gap between theoretical aspects of pavement design and observed performance of pavement structure through experimentations and experiences. With the availability of a large database on traffic characteristics, pavement material properties and performance assessment cards of existing pavements, a more comprehensive mechanistic–empirical pavement design guide (MEPDG) was provided by NCHRP (2004). MEPDG (AASHTO, 2008) is fundamentally different from AASHTO (1993) in two ways:

1. It uses multiple performance indicators.
2. It uses a direct relationship between structural design, materials, construction, climate and traffic and pavement management system.

MEPDG is an iterative procedure in which the output is pavement distress and smoothness, and not the thickness of the pavement layers. The analysis is performed in three stages. In the first stage, local site conditions such as traffic data, climate and subgrade are considered for providing a trial design as per AASHTO (1993) or any local guidelines/codes to be followed. The trial design is then evaluated for adequacy through prediction of distress and smoothness and fixing the performance criteria and reliability value. The inputs for assessing the performance of the trial design are broadly grouped into six categories: project-related information, design criteria, climate, traffic, layering and material properties. The designer considers different design features and materials for fixing the desired performance level and optimizes the outcome. In the second stage, MEPDG software is used for the purpose, and the performance indicators are pavement distress and IRI (international roughness index) over the design life. A trial design is finalized when each of the performance indicator criteria at the chosen reliability level is satisfied. MEPDG comprehensively includes the transfer function and regression model to predict performance indicators. The third stage of the engineering analysis includes life-cycle cost analysis. A detailed discussion on the topic is available in MEPDG, provided by AASHTO (2008). On similar lines, Muga et al. (2009) provided an integrated framework for life-cycle assessment and life-cycle cost analysis of concrete pavements by studying environment and economic impacts while substituting different percentage of fly ash and slag.

It is important to mention here that any mechanistic approach that involves FEM/FDM-based software for performance assessment of pavement structure considers input material properties as uniformly constant. A more realistic approach would be considering the spatial variability modeling of the material properties and then studying its influence on the performance. The present study demonstrates the consideration of influence of spatial variable modeling of input parameters on the performance assessment of a flexible pavement in reliability analysis framework, and the authors believe that it may provide sufficient input to researchers and experts working in the transport infrastructure field to incorporate the spatial variability modeling concept in their respective fields of pavement analysis and design.

For demonstration purpose, reliability analysis of the three-layer flexible pavement is carried out for the following two cases:

1. without consideration of spatial variability modeling; and
2. with consideration of spatial variability modeling procedure.

Results are compared and discussed to highlight the importance of incorporating spatial variability modeling in pavement analysis and design procedure. For the performance assessment in reliability-based approach, two most commonly adopted failure modes, i.e.
fatigue and rutting, are considered. It is well understood that critical locations for the computation of fatigue cracking and permanent deformation (rutting) in layered flexible pavements are identified at the bottom of the asphalt layer (Saal and Pell, 1960) and at the top of the subgrade layer (Kerkhoven and Dormon, 1953), respectively.

As shown in Figure 1, horizontal tensile strain ($\epsilon_t$) at the bottom of asphalt layer and vertical compressive strain ($\epsilon_c$) at the top of subgrade layer are computed using elastic layered analysis for fatigue and rutting cracking of the flexible pavement. Several research studies and organizations proposed an empirical relationship between $\epsilon_t$ and $\epsilon_c$ with a number of load repetitions to cause fatigue ($N_F$) or rutting ($N_R$) to predict failure. One of the most widely used empirical models provided by Asphalt Institute (1982) is:

No of load repetitions for fatigue failure ($N_F$): 

$$N_F = 0.0796(\epsilon_t)^{3.201}(E)^{-0.854} \quad (1)$$

No of load repetitions for rutting failure ($N_R$):  

$$N_R = 1.365 \times 10^{-9}(\epsilon_c)^{-4.477} \quad (2)$$

It should be noted that computation of compressive and tensile strains at critical locations of pavement structure through numerical analysis procedure is dependent on the input parameter, i.e. modulus of elasticity of the pavement layers. Uncertainty in the input parameters, measured in terms of statistical parameters, mean and variance and its spatial variation in 2D or 3D space brings variations in the computation of compressive and tensile strains, which in turn brings the uncertainty in the accurate prediction of $N_F$ and $N_R$. With advancements in the computing facilities and availability of high-end computers, it has now been possible to incorporate more rigorous and rational procedures that can take into account the uncertainty and spatial variation of input parameters in predicting the performance of the pavement structure.

As it is understood that structural design of pavement, i.e. determination of thickness of different layers existing over subgrade, depends on various input parameters related to traffic conditions and material characteristics of different layers, including subgrade, uncertainty in estimation of these input parameters brings uncertainty in predicting the pavement strength and deciding upon the appropriate thickness of different layers. Under these circumstances, questions that often arise are:

1. Is the thickness of the pavement provided appropriate?
2. What thickness will be appropriate with due consideration of uncertainty and variability in parameters to be used for reliability-based design?
In recent years, reliability analysis-based performance assessment of civil and infrastructure projects is gaining ground because of its capability to take into account the uncertainty and variability in input parameters in a mathematical framework and providing a rational approach in decision making. Alsherri and George (1988) developed a reliability-based model for pavement performance through Monte Carlo simulation and empirical design equations proposed in AASHTO design guidelines. Li et al. (1997) used the probabilistic concept to propose a pavement performance prediction model with the help of time-related non-homogeneous Markovian transition probability matrices through Monte Carlo simulations and updating the predicted pavement performance using the Bayesian updating technique. Hong and Somo (2001) suggested an approach for predicting the performance of flexible pavement in probabilistic framework. Stochastic input parameters considered for the analysis were “net traffic load growth” and “environmental actions”, using Ontario Pavement Analysis of Cost (OPAC) model, performance of flexible pavement was assessed in terms of output parameter, i.e. “riding comfort index” (RCI). Hong and Wang (2003) demonstrated how a simple probabilistic concept can be used in predicting the pavement performance with the help of a non-homogenous continuous Markov chain in conjunction with the flexible pavement deterioration models in the OPAC and in AASHTO. Wang and Hong (2004) suggested partial safety factors through first-order reliability method (FORM) and simulation technique for designing or assessing flexible pavements with due consideration of uncertainty in material properties and geometry of pavement, as well as in traffic and environmental conditions. Maji and Das (2008) addressed reliability issues in bituminous pavement design, based on mechanistic–empirical approach and suggested a methodology for designing a pavement with overall reliability. Deshpande et al. (2010) proposed reliability based model for flexible pavements that takes into account the effect of overlay design considering fatigue cracking and rutting. Chou and Li (2011) demonstrated how reliability analysis can be used in decision-making for maintenance and rehabilitation activities, as well as optimization of roadway maintenance plans. Retherford and McDonald (2012) addressed the issue of uncertainty in MEPDG and incorporated reliability analysis to investigate the effect of these sources of uncertainties in a typical flexible pavement design. Dilip et al. (2013) discussed procedure for evaluating system reliability analysis of flexible pavements by considering mechanistic–empirical models and interdependency of fatigue and rutting failure modes through correlation. Luo et al. (2014) proposed reliability-based mechanistic–empirical pavement design considering fatigue and rutting empirical models with the help of spreadsheets and FORM. Ma et al. (2015) used Freeze–Thaw (F–T) deterioration model for the reliability analysis of asphalt pavement in cold regions. These literature reviews suggest that reliability and probabilistic concepts have been used or implemented in various ways for performance assessment or design of flexible pavements, as well as management of funds for maintenance and rehabilitation work. Dinegda and Birgisson (2015) used LRFD (load and resistance factor design) based procedure for the reliability based calibration for fatigue cracking. A combination of central composite design-based response surface approach and a first-order reliability method was used for the reliability analysis. Kalita and Rajbongshi (2014) established the distribution and parameters of distribution for the input parameters that is pavement life and traffic repetitions and the study suggested that irrespective of distribution of input parameters, the output response, i.e. pavement life and damage parameters follow log-normal distribution. A factor of safety-based deterministic reliability analysis approach using mechanistic–empirical approach and fatigue and rutting failure criterion was suggested. Wojtkiewicz et al. (2011) provided a software framework for the probabilistic modeling of pavement performance by combining deterministic performance models presented by MEPDG and
probabilistic analysis tool to predict pavement performance under given environment of uncertainty in AC concrete mix design.

Objectives of the present study
In the present study, reliability-based performance assessment of layered flexible pavement is demonstrated through a combination of finite difference-based numerical analysis, empirical predictive models for rutting and fatigue failure, Monte Carlo simulations (MCS) and reliability analysis through FORM. In the analysis, input property, i.e. elastic modulus of sub-grade soil and elastic modulus of pavement layers, is considered as spatially varying in 2D space, and its numerical modeling is done through FISH function available as an in-built option in commercially available finite difference code Fast Lagrange Analysis of Continua (FLAC). The results of the reliability analysis of the pavement layers, with and without consideration of spatial variability modeling of input properties (elastic modulus), are compared and discussed. Parametric study on scale of fluctuation is carried out to investigate the importance of high correlation structure and uniformity in input parameters for achieving the high performance level of the pavement structure.

Reliability analysis
In reliability analysis, input parameters are treated as random variables and the output response, which will also be a random variable, is studied in probabilistic framework to assess the performance of the structure or system or design a system with expected performance level. Generally, in the reliability analysis, input parameters are treated as normally or log-normally distributed continuous random variables. Performance assessment of structure or structural component is made through an index known as reliability index ($\beta$). Quantitative assessment of uncertainty in the input parameters relies on number ($n$) of measured data ($x_i$) and unbiased estimate of sample mean ($\mu$) and sample variance ($\sigma^2$).

Parameters of assumed probability distribution function ($pdf$) are derived from $\mu$ (sample mean) and $\sigma$ (standard deviation). Coefficient of variation ($\%$), which is defined as the ratio of standard deviation ($\sigma$) to the sample mean ($\mu$), is commonly used to quantify the uncertainty because of being dimensionless and providing a meaningful measure of relative dispersion of data about the mean. In case of absence of site-specific data, coefficient of variation in an input parameter can be taken from the published literature (Lacasse and Nadim, 1996; Duncan, 2000; Uzielli et al., 2007). Detailed discussion on probabilistic concepts and different methods of reliability analysis are available in literature, such as, Ang and Tang (1984), Kottegoda and Rosso (1997) and Baecher and Christian (2003). USACE (1997) made specific recommendations on performance acceptability of infrastructure projects in terms of reliability index ($\beta$) or corresponding probability of failure ($p_f$).

As shown in Figure 2, for ensuring high performance, a reliability index ($\beta$) of 5.0 is acceptable. For above average performance, reliability index ($\beta$) value should be at least 3.0. Estimation of reliability index requires data on mean and variance of the output response and expected performance level. In case of absence of sufficient experimental data, MCS is performed to obtain information on mean and variance in the output response through numerical experimentation or analytical approach or use of design charts. Numerical experimentation is done through finite element or finite difference-based numerical analysis procedures. Input parameters are needed to analyze the pavement structure and read the strain level at critical locations. In the present study, elastic analysis of the pavement structure is carried out to study the response of the pavement under given loading condition and the input parameter for the elastic analysis is modulus of elasticity of the pavement.
layers and Poisson’s ratio. It should be noted that properties do vary in space and consideration of spatial variation of input properties in the analysis and design procedure very well capture the behavior or response of structure or system in a realistic manner.

**Spatial variability modeling**

In recent years, it has been realized that uncertainty in the input parameters cannot be completely analyzed by second moment statistics alone, i.e. mean ($\mu$) and variance ($\sigma^2$), in situations where properties vary in 2D or 3D space. To model spatial variation of the input parameters, a third statistical parameter, i.e. correlation distance or scale of fluctuation ($\delta$), was proposed by Vanmarcke (1983). Scale of fluctuation defines the distance in a space within which the properties of strongly correlated. Detailed discussion on random field concepts and spatial variability modeling procedure through finite element analysis along with its application in different fields of civil and infrastructure projects are available in Fenton and Griffiths (2008). The procedure for implementing random field modeling of spatially varying properties in 2D space is discussed below.

Assuming that elastic modulus ($E$) of materials in different layers of pavement structure is to be modeled as spatially varying parameter in a 2D space. For a log-normally distributed continuous random field for $E$ with its mean ($\mu_E$), standard deviation ($\sigma_E$) and scale of fluctuation ($\delta$), the following equation is used:

$$E(\bar{x}) = \exp\left\{ \mu_{\ln E}(\bar{x}) + \sigma_{\ln E}(\bar{x}) \cdot G(\bar{x}) \right\}$$  \hspace{1cm} (3)

In the above equation (3), $\bar{x}$ is the spatial position at which $E$ is desired and $G(\bar{x})$ is normally distributed random field with mean zero and variance one. The values of $\mu_{\ln E}$ and $\sigma_{\ln E}$ are obtained using log-normal distribution transformations given as:

$$\mu_{\ln E} = \ln \mu_E - \frac{1}{2} \sigma_{\ln E}^2$$  \hspace{1cm} (4)

$$\sigma_{\ln E}^2 = \ln \left( 1 + \frac{\sigma_E^2}{\mu_E^2} \right) = \ln \left( 1 + COV_E^2 \right)$$  \hspace{1cm} (5)
Griffiths and Fenton (2007) suggested that the correlation coefficient, $\rho_E(\tau)$, between log-normally distributed properties at two points, namely, $\ln E(x)$ and $\ln E(x + \tau)$, separated by $\tau$, is an exponentially decaying function of separation distance and it is defined as:

$$
\rho_E(\tau) = \exp\left(-\frac{2\tau}{\delta}\right)
$$

(6)

where, $\tau = |\hat{x}_1 - \hat{x}_2|$ is the absolute distance between the two points. For spatial variability modeling, the auto-correlation matrix ($L$) is decomposed into the product of a lower triangular matrix and its transpose by Cholesky decomposition (Press et al., 2002):

$$
L \cdot L^T = \rho_E(\tau)
$$

(7)

For the matrix $L$, the correlated standard normal random field is obtained as:

$$
G_i = \sum_{j=1}^{i} L_{ij} Z_j, \quad i = 1, 2, 3 \ldots n
$$

(8)

where, $Z_i$ is the sequence of independent standard normal random variables.

For the 2D analysis of pavement structure, the correlation distances in both the directions are assumed as same considering isotropic correlation structure, which is considered to be sufficient to understand the basic stochastic behavior as discussed by Griffiths et al. (2002).

**Implementation of random field**

The auto-correlation matrix is first generated using equation (6). The lag distance ($\tau$) is considered as the center-to-center distance of the constitutive grids. Figure 3 depicts the method of evaluation of auto-correlation matrix with discretization of finite difference grid. If center-to-center distance between the two grids, say, 1 and 2, is $dx$, then the auto-correlation between these two grids is evaluated by putting $\tau = dx$. Similarly, auto-correlation of grid 1 with 3, 4, 5 is established by placing $\tau = 2 \times dx$, $3 \times dx$ and $4 \times dx$, respectively and auto-correlation for grid 1 with 31, 32, 33 is given by $dy$, $\sqrt{dx^2 + dy^2}$ and $\sqrt{(2dx)^2 + dy^2}$, respectively, and so on. Hence, the values in the first row of the

![Figure 3. Discretization of finite difference grid in the random field modeling](image-url)
auto-correlation matrix are the auto-correlation coefficients between grid 1 and other grids, and it leads to 900 values in a row for a grid size of 30 x 30. Considering all the grids, the auto-correlation matrix has a size of 900 x 900. After establishing auto-correlation matrix, it is decomposed into lower and upper triangular matrices (L and L^T) as discussed in Cholesky decomposition technique. The correlated standard normal random field (G) is generated through a sequence of independent standard normal random variables (with zero mean and unit standard deviation) and decomposed auto-correlation matrix using equation (8). The realization of log-normally distributed elastic modulus (E) value at each grid location is obtained through transformation equation (3) for a specified mean and standard deviation of parameter E. The calculation procedure is implemented in FLAC2D via “FISH” function available as an inbuilt option in the code (FLAC, 2015).

FLAC 2D is a commercially available numerical tool used for continuum analysis of geotechnical problems in 2D space. It is a powerful tool that uses an explicit finite difference formulation to model complex behaviors, such as, staged construction, large displacements and strains and non-linear constitutive behavior. The program provides 17 built-in constitutive models, simulation of groundwater flow, coupled mechanical-flow calculation with pore pressure generation, structural elements for modeling soil nailing for example, incorporating statistical distribution of input properties, and a built-in scripting language (FISH) that can handle virtually all aspects of program operation, including user-defined constitutive models and other variables. For detailed discussion on the topic, reader may refer to user’s manual (FLAC, 2015).

Figure 4 shows typical realization of spatial variability modeling of shear modulus parameter with scale of fluctuation values 0.01 m, 0.50 m, 5.0 m and 10.0 m. It can be noted that the field is more erratic with low value of scale of fluctuation, and with increase in scale of fluctuation values, the material achieves more homogeneity as the properties at far locations are also correlated.

Monte Carlo simulation (MCS)
Owing to random field process, each realization of 2D log-normally distributed random field for E (given mean, standard deviation and scale of fluctuation) will be different. Hence, for every realization of the parameter E, the output response will also be different. In the present study, the output response is the horizontal tensile strain at the bottom of the surface layer (ε_t) and vertical compressive strain (ε_c) at the top of the subgrade layer for fatigue and rutting failure cases. Consequently, using equations (1) and (2) for fatigue and rutting analysis, for each realization, the number of load cycles for fatigue (N_F) and rutting (N_R) failure will be different. Monte Carlo simulations are performed in which analysis is repeated N (sample size) number of times and output response is recorded for each simulation. After simulating and recording the data for ε_t and ε_c for N number of simulations and predicting the number of load repetitions for N_F and N_R for each realization, the statistical parameters, i.e. mean and variance in N_F and N_R are obtained through simple statistical calculations using N number of data sets available for N_F and N_R and reliability analysis is carried out in terms of reliability index (β).

Reliability index (β)
If C and D is the capacity and demand of a system and performance function is defined as g0 = C/D; for log-normally distributed C and D, the reliability index (β) is obtained as:
where, $\mu_C$, $\mu_D$ are the mean and $\delta_C$, $\delta_D$ are coefficient of variation in $C$, and $D$, respectively. In the present study, $N_F$ (with respect to fatigue cracking) or $N_R$ (with respect to rutting) is considered as the capacity ($C$) of the pavement structure. Demand ($D$) is the design traffic load ($N_D$). Estimation of reliability index ($B$) through equation (9) will require information on $\mu_C$, $\mu_D$, $\delta_C$ and $\delta_D$ in $C$, and $D$. Mean ($\mu_C$) and coefficient of variation ($\delta_C$) in $N_F$ and $N_R$ are obtained through numerical data collected from Monte Carlo simulations. Demand ($D$), i.e. design traffic

\[
B = \frac{\ln \left( \frac{\mu_C}{\mu_D} \sqrt{\frac{1+\delta_D^2}{1+\delta_C^2}} \right)}{\sqrt{\ln \left( \frac{1+\delta_D^2}{1+\delta_C^2} \right)}}
\]
load is estimated from the analysis of existing data on traffic flow and other characteristics of the pavement system. In the present study, design traffic load is taken as 40 MSA and coefficient of variation in the demand (δ) is assumed as 40 per cent (Maji and Das, 2008).

**Results of the analysis and discussion**

*Case A: without spatial variability modeling of input parameters*

The procedure first involved the estimation of trial thickness of flexible pavement layers through existing guidelines. In the present study, IRC:37-2001 is used to determine the total thickness of the flexible pavement layer based on the assumed CBR (California bearing ratio) value of subgrade soil and design traffic load (in MSA). Thickness of different layers of flexible pavement, i.e. base course and surface course, is then determined with the help of design catalogs prepared for designed traffic load. Other input parameter is the elastic modulus of different layers of flexible pavement. In the present study, mean CBR of subgrade layer is assumed as 10 per cent. The mean values of elastic modulus of different layers of flexible pavement are presented in Table I.

Following the guidelines provided in *IRC: 37-2001*, for the mean design traffic load of 40 MSA, thickness of base course and surface layer is obtained as 450 mm and 130 mm, respectively.

Once the thickness of different layers of the flexible pavement is fixed, consideration of uncertainty in the input parameter, i.e. elastic modulus of pavement layers, and its influence in the performance assessment of pavement are studied through reliability analysis. Uncertainty in the input parameters are measured in terms of a non-dimensional parameter, coefficient of variation (CoV per cent) and typical values of coefficient of variation in the elastic modulus of different pavement layers are indicated in Table I. It can be noted that one can always work with different value of CoVs based on available experimental records or literature support.

Assuming that the input parameters, i.e. elastic modulus of pavement layers, follow a log-normal distribution, the first step involved in the MCS is to generate N number of data sets of input parameters that follows the given distribution and the parameters of distribution are obtained from the mean and variance in the data. In the present study, 100 random numbers were generated for the elastic modulus values of each layer with given mean and coefficient of variation as indicated in Table I to perform MCSs. It should be noted that large number of simulations provide better accuracy, but it is time-consuming when MCS is integrated with the numerical analysis. One can always work with large number of simulations, if desired so. Haldar and Sivakumar Babu (2007) also suggested 100 simulations in their study.

<table>
<thead>
<tr>
<th>Description</th>
<th>Material behavior</th>
<th>Unit weight (kg/m³)</th>
<th>Poisson’s ratio (ν)</th>
<th>Design (E) value, MPa</th>
<th>CoV (%)</th>
<th>Reference (IRC:37-2001)</th>
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<tr>
<td>Subgrade layer</td>
<td>Elastic</td>
<td>1,750</td>
<td>0.35</td>
<td>76.8</td>
<td>34</td>
<td>E₃ = 17.6(CBR)^0.64</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>assumed CBR = 10%</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>E₂ = 0.2(E₃)(h)^0.45</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td>h = thickness of the base course (450 mm)</td>
</tr>
<tr>
<td>Base course</td>
<td>Elastic</td>
<td>1,840</td>
<td>0.35</td>
<td>240</td>
<td>34</td>
<td>MOST (1995)</td>
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<td></td>
<td></td>
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<td></td>
<td>For 80/100 bitumen at temp 30°C</td>
</tr>
<tr>
<td>Surface course</td>
<td>Elastic</td>
<td>2,400</td>
<td>0.40</td>
<td>1,455</td>
<td>28</td>
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</tr>
</tbody>
</table>

**Note:** Specifications for road and bridge works (third revision), 1995, Ministry of Surface Transport (Roads wings), published by IRC, New Delhi

**Table I.** Design values and CoV (%) of elastic modulus of different layers of flexible pavement
Once 100 random numbers are generated for the elastic modulus of different pavement layers, each set of these parameters is used as an input for the numerical analysis of the pavement layer.

Figure 5 shows typical cross-section of pavement structure along with boundary conditions, wheel configuration (spacing 31 cm) and wheel pressure (550 kPa) adopted for the numerical analysis of the pavement structure. Through numerical analysis, tensile strain at the bottom of surface course \( (\varepsilon_t) \) and compressive strain \( (\varepsilon_c) \) at the top of the subgrade layer are computed, and the values of \( N_F \) and \( N_R \) are estimated through equations (1) and (2). The procedure is repeated 100 times, i.e. numerical simulation of the pavement layer is performed for these 100 sets of input parameters and the compressive and tensile strain at critical locations are computed to find the \( N_F \) and \( N_R \) values. Hence, 100 data sets are now available for estimation of mean and variance in \( N_F \) and \( N_R \) through simple statistical calculations.

The statistical information, i.e. mean and coefficient of variation in \( N_F \) and \( N_R \) are further used in estimating the reliability index values with respect to fatigue \( (\beta_F) \) and rutting \( (\beta_R) \). For the case analyzed, following the procedure, mean and coefficient of variation in \( N_F \) and \( N_R \) are obtained as 730 MSA (CoV = 62.5 per cent) and 912 MSA (CoV = 102.2 per cent), respectively. With reference to equation (9), considering the following parameters, i.e. mean of \( N_F \) or \( N_R \) as mean capacity \( (\mu_C) = 730 \) MSA (fatigue) or 972 MSA (rutting); coefficient of variation in capacity \( (\delta_C) = 0.625 \) (fatigue) or 1.12 (rutting); mean demand \( (\mu_D) = 40 \) MSA; CoV in the mean demand \( (\delta_D) = 0.4 \), the reliability index values with respect to fatigues failure \( (\beta_F) \) and rutting failure \( (\beta_R) \) are obtained as 4.06 and 3.12.

The reliability index values suggest that under the given environment of uncertainty the performance of the pavement will be above average, as the reliability index values in both the cases are more than 3.0. The same problem will now be solved with due consideration of spatial variation of input parameter.

**Case B: with spatial variability modeling of input parameter**

Figure 6 explains the step-by-step procedure for performing the reliability analysis of the layered flexible pavement structure (subgrade, base and surface layer) with spatial variability modeling of input parameter, numerical analysis for strain calculation at critical locations, empirical models for predicting \( N_F \) and \( N_R \), MCSs and FORM for reliability analysis. Mean and coefficient of variation in the input parameters are taken from Table I. For spatial variable modeling of the input parameter, different values of scale of fluctuation \( (\delta) \) are chosen, i.e. 0.01 m, 0.50 m and 5.0 m and 10m, to not only study the influence of spatial variation of input parameter but also investigate the effect of correlation structure on the performance of the pavement structure.

![Figure 5. Typical cross-section of pavement structure with load configuration and boundary conditions](image-url)
Initially, for analyzing a particular case, the scale of fluctuation is taken as 0.5 m. Following the procedure explained in the previous section, the input parameter E is modeled as spatially varying parameter in a 2D space. It should be noted that each realization of the input parameter is random in nature; hence, every simulation will generate a different realization with given mean, coefficient of variation and scale of fluctuation in the input parameter. For each realization, through numerical analysis, tensile strain at the bottom of surface course (\( \varepsilon_t \)) and compressive strain (\( \varepsilon_c \)) at the top of the subgrade layer is again estimated and correspondingly the value of \( N_F \) and \( N_R \) are calculated from equations (1) and (2). The procedure is repeated \( N \) no of times to perform MCSs, i.e. 100 realizations of spatial variability modeling of elastic modulus of different layers through numerical modeling procedure and analysis for strains at critical locations. For each case, the values of \( N_F \) and \( N_R \) are obtained and mean and coefficient of variation in \( N_F \) and \( N_R \) are estimated from 100 numbers of data set. The statistical information, i.e. mean and coefficient of variation in \( N_F \) and \( N_R \) so obtained are used to estimate the reliability index values with respect to fatigue (\( \beta_F \)) and rutting (\( \beta_R \)).

For the case analyzed, the mean values of compressive strain at the top of the subgrade layer and tensile strain at the bottom of the surface layer are obtained as \( \varepsilon_c = 13.42 \times 10^{-7} \) and \( \varepsilon_t = 18.11 \times 10^{-7} \), respectively. The coefficients of variation in the mean strain are obtained as...
27 per cent in both the cases. Further, mean and coefficient of variation in \( N_F \) and \( N_R \) are obtained as 520 MSA (CoV = 97.5 per cent) and 724 MSA (CoV = 138.6 per cent), respectively. Considering the following input parameters: mean of \( N_F \) or \( N_R \) as mean capacity (\( \mu_C \)) = 520 MSA (fatigue) or 724 MSA (rutting); coefficient of variation in capacity (\( \delta_C \)) = 0.975 (fatigue) or 1.39 (rutting); mean demand (\( \mu_D \)) = 40 MSA; CoV in the mean demand (\( \delta_D \)) = 0.4, the reliability index values with respect to fatigues failure (\( \beta_F \)) and rutting failure (\( \beta_R \)) are obtained as 2.55 and 2.20. It can be noted that with spatial variability modeling of the input parameter, the reliability index values for fatigue and rutting is lower than the corresponding values obtained for the case with no spatial variability modeling of input parameter.

If it is assumed that the mean values of \( N_F \) and \( N_R \) are the indicative of mean values of input parameters adopted for the conventional analysis in which properties are considered as uniformly constant then the values of \( N_F \) and \( N_R \) are quite high when compared to design traffic load of 40 MSA. Conventionally, these numbers indicate good design and ensure a very high performance level of the pavement structure throughout the design life. With due consideration of uncertainty, as well as spatial variability modeling of the elastic modulus of different layers, it is remarked that the results of the reliability analysis presents a different scenario. Through reliability analysis, performance of the pavement structure is assessed as below average because of high coefficient of variation obtained in the capacity of the pavement structure. Hence, a revised design should be suggested with either increased thickness of the pavement layers or improved properties or a combination of two. It has been observed that consideration of uncertainty in the input parameters and reliability analysis through spatial variability modeling procedure provides more comprehensive treatment to the problem of analysis, design and performance assessment of pavement structure.

Further analysis is undertaken after considering other values of scale of fluctuations. The results of the reliability analysis are summarized in Table II. It can be noted that with increase in scale of fluctuation, the reliability index values increases. It may be because the material properties achieve more uniformity with higher correlation structure and this indicates advantage to achieve economical design when the properties are highly correlated. The results of the analysis suggest that achieving uniformity in the properties ensures high performance level of the pavement structure and in field it can only be achieved through high quality control.

### Conclusion

- Conventional approach in which input properties are considered as uniformly constant does not provide a realistic treatment to the analysis and performance assessment of flexible pavement structure in which properties not only have inherent variations but also show variation in space.
- Although, combining numerical analysis, with spatial variability modeling of input parameters, Monte Carlo simulation and FORM for the reliability analysis of flexible

<table>
<thead>
<tr>
<th>Scale of fluctuation</th>
<th>Fatigue (( \beta_F ))</th>
<th>Rutting (( \beta_R ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta = 0.01 ) m</td>
<td>2.48</td>
<td>2.11</td>
</tr>
<tr>
<td>( \delta = 0.50 ) m</td>
<td>2.55</td>
<td>2.20</td>
</tr>
<tr>
<td>( \delta = 5.00 ) m</td>
<td>2.85</td>
<td>2.38</td>
</tr>
<tr>
<td>( \delta = 10.0 ) m</td>
<td>3.01</td>
<td>2.54</td>
</tr>
</tbody>
</table>

**Notes:** Traffic demand \( D = 40 \) msa; CoV in demand = 40%
pavement is, mathematically, cumbersome, yet it provides a logical step towards performance based analysis and design of pavement structure using mechanistic–empirical approach.

- With consideration of spatial variability of input parameter, the performance index measured in terms of reliability index ($\beta$) is slightly reduced when compared to the reliability index values obtained for the same pavement structure without consideration of spatial variation of input parameters.

- Consideration of variability- and reliability-based analysis clearly demonstrated that the performance of the pavement structure considered in the present study under the given circumstances is expected to be below average which was otherwise deemed satisfactory from conventional approach, as well as without consideration of spatial variation of input parameters.

- Scale of fluctuation, a mean to measure the correlation of spatial varying properties, plays a vital role in the reliability-based analysis, and it reduces the variance in the properties, thereby increasing the reliability of the system.

- Proper consideration of correlation structure may prove to provide a more economical design, and issues of variation in the properties also suggest achieving more uniformity in the properties during construction phase with strict quality control measures, especially in pavement industry.

- Suggested guidelines and procedure for spatial variability modeling through numerical analysis can easily be incorporated in the existing mechanistic approach, as well as mechanistic–empirical approach, to give a more realistic treatment to spatially varying properties of the pavement structure.

- A more realistic treatment would be considering spatial variation of input parameters in a 3D space with consideration of scale of fluctuation having different values in a 3D space along $x$-, $y$- and $z$-axes. The present study demonstrates the powerful technique to handle the problem in a rigorous mathematical framework to take decisions in a more rational manner.

References


USACE (1997), “Risk-based analysis in geotechnical engineering for support of planning studies, engineering and design”, Department of the Army, USACE, Washington, DC, 20314-100.


**Further reading**


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A multi-criteria decision-making approach to minimising fire risk in detached house designs

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Abstract

Purpose – House fire risk would be minimised if fire safety principles were incorporated at the design stage. This issue is rarely addressed in the literature. The purpose of this study is to propose a multi-criteria decision-making framework to evaluate fire risk of detached house designs in the United Arab Emirates and countries of similar cultural background.

Design/methodology/approach – The framework was developed based on function areas where (detached) house fires start, expert opinion and recommendations derived from the published literature on residential fire safety. This framework was applied to a sample of ten public detached house designs to check the applicability of the framework and to determine how safe these designs are from a fire safety perspective.

Findings – The proposed framework is proven to be an effective preliminary fire risk evaluation tool of detached house designs, and more research is needed in this area.

Research limitations/implications – The proposed framework is an encouraging first step in incorporating fire risk minimisation at the design stage of detached houses based on determining the preferred location of function areas but requires further development and validation, especially in other design settings.

Practical implications – The proposed framework is an initial endeavour in helping designers of detached houses to minimise fire risk and its potential effects on residents.

Originality/value – This research proposes a way to minimise fire risk at the design stage of detached houses.

Keywords Multi-criteria decision-making, Fire safety, Detached house design, House function areas, Residential fire causes

Paper type Conceptual paper

1. Introduction

1.1 Background

Any completed residence should enhance the quality of life for its occupants as well as provide a safe environment to those occupants (Husin et al., 2012). Safety measures aim to protect people from any harm. If safety is incorporated at the design stage before houses are constructed, the potential to reduce harm and injury would be high and long lasting. Also, if a culture of safety develops among the house construction industry and its customers, safe home designs would become prevalent (Alhajeri, 2011).

Fire is critical to the development of human society and has become an important part of human civilisation. Nevertheless, fire poses a significant threat to life and property. Society has responded to the threat of fire in buildings in many ways, including fire department intervention, insurance, building regulations, education on fire hazards, controls on the use of materials and products in residential buildings and designing buildings such that they resist the effects of fire (Xin and Huang, 2013). There is an inevitable fire risk in every
designed building. This issue occasionally attracts public attention when fatal fires occur, as was the case in the Kiss nightclub fire in Brazil in January 2013, which led to the death of 241 people (Stollard, 2014).

The main objective of fire safety is to minimise the risk of igniting fires as well as to protect any given building and its residents from the resulting smoke and heat. Fire safety normally incorporates both the safety of people and the protection of property (Alqassim and Daeid, 2014; Stollard, 2014). Nevertheless, fire safety objectives in buildings may vary based on the building’s type of use, structure and height (Buchanan, 2001). Therefore, buildings should be designed in a way that reduces fire risk and gives occupants the maximum chance to escape unharmed in case of fire (Qianlia and Weib, 2012).

This study considers the UAE as a base country. Like in many other developing countries, published studies that discuss residential fire safety are scarce. In the only published study found in the literature that examined residential fire risk in UAE, Ahmed (2011) interviewed a sample of 60 Emirati families living in selected public housing prototypes on fire safety related issues. The majority (78.3 per cent) of interviewed families pointed out that their houses were not provided with any means of fire protection, including smoke detectors, alarms or escape routes in case of emergency. This highlights the importance of incorporating fire safety principles at the design stage of any house and the responsibility of architects and engineers to minimise fire risk at the design stage as was stipulated by Stollard (2014).

The current work aims to develop an evidence-based framework to evaluate fire risk of detached house designs in UAE and countries of similar cultural background. It is thought that this framework would help designers to minimise fire risk at the design stage and evaluate existing designs. This would ultimately lead to safer houses and give occupants a greater chance of surviving unharmed when fires erupt.

1.2 Relevant house design principles
In this section, a brief introduction to general house design principles in UAE (and possibly other countries of similar cultural background) and function areas within these houses is given.

Houses in various countries come in many types, but share common function areas such as living rooms, dining rooms, kitchens, bedrooms and bathrooms (Chandler et al., 2005). Design of houses in UAE is impacted by a number of cultural (mainly Islamic) principles such as privacy and hospitality. Muslim houses usually involve four main layers of privacy:

1. privacy between neighbouring dwellings;
2. privacy between males and females;
3. privacy between family members inside a home; and
4. individual privacy (Othman et al., 2015).

Accordingly, a Muslim house should have, if possible, more than a single circulation system. This is to facilitate the necessary and unobstructed movement of people inside the house, and from inside the house to its outside and vice versa, without putting the privacy of any user of the house at risk. As hospitality domains should be considered in any house design (Othman et al., 2015), there should be a space designated for guests in every house (Omer, 2014). They include a public hospitality function area (room) for male guests (also known as majlis in UAE and some other Arab countries) and semi-public hospitality function area for
female guests (also known as *salon* in UAE and some other Arab countries). The male guest room (MGR) is usually separated from the house and has its entrance towards the road so that the regular domestic life activities inside the house are not disrupted. Preferably, there should be a toilet close to the MGR. The female guest room (FGR) usually lies close to the middle of the house and is connected to the kitchen. If there are no guests at home, both function areas could be used for other domestic purposes (Omer, 2014). However, because of limited space, some houses might have only one guest room for all guests.

Family space, where the family gathers for entertainment and dining, is usually separated from other areas in the house (Othman *et al.*, 2015). Also, living quarters for a maid is usually assigned near those spaces that are considered least sensitive for the privacy of both the maid and the family in the household. A preferred solution is where the maid gets a room with its own bathroom at the rear of the house where a kitchen, a store and maybe a back yard are located. Kitchens should be placed in the deepest and most secure place in the house, away from the public eye (Omer, 2014). Stores are considered to be a part of the space that should be implemented into all types of housing (Alkhalidi, 2013).

1.3 *Function areas within UAE houses*

The aim of this current research is to put forward a framework that would help in evaluating house designs from a fire safety perspective with the ultimate aim of minimising fire risk. This is done by evaluating the design of the house interior based on the desired proximity of the different function areas that exist in houses taking fire risk and functionality considerations into account. Based on the above-mentioned design principles of houses in UAE and in countries of similar cultural background and according to Ragette (2001), function areas in a typical Emirati house might include most or all of the following:

- FGR;
- MGR;
- bedroom;
- guest bedroom (GBR);
- family room (including dining area);
- maid’s room;
- kitchen;
- storage room; and
- bathroom.

It is vital to note here that this study assumes that the average size house in UAE is between 2,000 and 6,000 ft². Houses bigger than 6,000 ft² are not considered here as they would include more function areas (like office and pantry) than those stipulated in this study.

2. *Methodology for developing a framework for evaluating fire risk in house design*

Multi-criteria decision-making methodology (MCDM) involves developing methods that help in decision-making while taking multiple criteria into consideration. Such criteria usually involve quantifiable ones (e.g. historical data) as well as non-quantifiable ones (e.g. expert opinion). This sometimes makes the decision maker feel obliged to compromise when making decisions because of the possible conflict between these criteria. MCDM
methodology can be applied to many areas, including agriculture management, evaluation of technology investment and energy planning (Pohekar and Ramachandran, 2004).

The proposed fire risk evaluation framework relies on three sources of information. The first source is house design guidelines on the proximity of function areas in houses from a fire safety perspective reported in the literature and in the fire code of practice. The second determines the house function areas where most fires start. The third is expert opinion on the desired proximity of function areas that would minimise fire risk in houses while taking the practical needs of the occupants into consideration.

2.1 Literature on minimising fire risk in house design

Most house fire safety studies published in peer-reviewed journals and books concentrated on design aspects related to multi-level residential buildings. Yet, some of the recommendations given in those publications can be applied to detached houses. In this section, a review of the concerned literature on detached houses is given together with some relevant literature on multi-level residential buildings.

The materials used to construct and finish houses play a very important role in any fire (Kobes et al., 2010). Concrete does not burn when it is exposed to fire and this is why it is considered fireproof (Wang et al., 2013). As reinforced concrete structures are the most common building form for houses in UAE, these structures are considered safe and designers need not worry about house structure itself from a fire safety perspective.

Another factor that affects any house fire outcome is how people behave in the case of fire. Human behaviour in this context is defined as “the action that people take based upon their perception of the situation, their intention to act, and the consideration involved before these actions are carried out” (Kobes et al., 2010). People have to be alerted and have to evacuate before the situation becomes untenable (Guillaume et al., 2014). In the design stage of any house, an evacuation model should be developed (Townsend, 2014). Also, escape routes and fire exits should be designed in a way that can help the home occupants to evacuate easily and as fast as possible (Buchanan, 2001). Moreover, the UAE Fire and Life Safety Code of Practice (Ministry of Interior, 2011) states that in residences of the size being considered in the current paper, there should be two exits or more and that the balance of exits should be established so that if one exit becomes blocked, the other shall be accessible.

Any house design should be done in a way that optimises the observational power of individuals in relation to any fire risk, including their ability to recognise, see, smell and feel fire signals (Graham and Roberts, 2000). Occupants usually use familiar routes inside houses which are the main entrances of the house. This, in turn, depends on the complexity of the building layout, availability of exits and the accessibility of the way towards these exits (O’Connor, 2005).

Another relevant topic mentioned in the literature is the existence of a protected route that should remain free from smoke and fire for a time adequate to allow any person anywhere in the building to escape to a place of reasonable safety, for example a protected area or stairway. So, escape routes should be designed to ensure the safety of people escaping from the building in case of fire (Department for the Environment, Heritage and Local Government, 2006).

The safety of house occupants in inner rooms forms another constraint reported in the literature that should be considered at the design stage. An inner room is a room where the only escape route is through another room (termed the access room). Inner rooms such as kitchens, dressing rooms, store rooms and bathrooms are a safety concern because of the risk of fire in the access room (North Norfolk District Council, 2014), which might make escaping dangerous. Therefore, the store room that contains significant quantities of
flammable materials and ready sources of ignition should be remote from the escape route. When a fire happens near the exit, the evacuation will be more difficult and dangerous. Ideally, bedrooms should be closer to the exit door than living areas or kitchen facilities (Neufert et al., 2002).

Another potential source of information is the national fire code of practice published and enforced by many countries. Usually, this code gives specific details on building design criteria like fire extinguishers and signs, minimum stair and door width, building materials, fire detection and alarm systems, emergency lighting, grade of fire resistance of openings, and size of openings. Nevertheless, and taking the UAE Fire and Life Safety Code of Practice (Ministry of Interior, 2011) as an example, such codes do not usually give specific house design guidelines on the proximity of function areas in houses from a fire safety perspective.

The previously mentioned literature on the design of houses and desired proximity of their function areas in a way that would minimise fire risk and optimise the likelihood of residents escaping unharmed in case of fires is summarised in Table I. It is clear from this table that no clear house design guidelines have been developed on the

<table>
<thead>
<tr>
<th>Publication</th>
<th>Purpose/methodology</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkhalidi (2013), Omer (2014), Othman et al. (2015) and Ragette (2001)</td>
<td>Investigating function areas in typical Muslim houses (such as UAE)</td>
<td>Design of houses in countries with Muslim majorities (such as UAE) have some unique features and constraints that need to be taken into consideration</td>
</tr>
<tr>
<td>Buchanan (2001) and Townsend (2014)</td>
<td>Effects of house design on fire safety</td>
<td>Fire safety principles should be incorporated at the design stage of houses to maximise safe escape for house residents during fire</td>
</tr>
<tr>
<td>Department for the Environment, Heritage and Local Government (2006) Graham and Roberts (2000)</td>
<td>Escape routes in cases of fire</td>
<td>Escape routes should be accessible, unobstructed and protected and should be designed accordingly</td>
</tr>
<tr>
<td>Kobes et al. (2010) and Wang et al. (2013)</td>
<td>Investigating the effects of house structure on fire propagation</td>
<td>Design of structures should enhance observational power of individuals of fire signals and escape routes</td>
</tr>
<tr>
<td>Neufert et al. (2002)</td>
<td>Residents accessibility to escape routes</td>
<td>Concrete house structures (like the ones used in UAE) do not burn and are considered fireproof and safer than other structures in case of fire</td>
</tr>
<tr>
<td>North Norfolk District Council (2014)</td>
<td>Escape routes from inner rooms (i.e where the only escape route is through other rooms)</td>
<td>Store rooms that might contain flammable materials should be put away from escape routes. Bedrooms should be closer to those routes exits than living areas or kitchens</td>
</tr>
<tr>
<td>O’Connor (2005)</td>
<td>People’s choice of escape routes in case of fire</td>
<td>Fire escape routes of inner rooms should be considered at the design stage of houses</td>
</tr>
<tr>
<td>Stollard (2014)</td>
<td>Checking house fire precautions in UAE by interviewing 60 Emirati families</td>
<td>Occupants usually use familiar exit routes. These routes should be sufficiently available and easy to recognise and access</td>
</tr>
</tbody>
</table>

Table I. Summary of relevant literature on the design of houses in relation to fire safety
proximity of function areas in houses from a fire safety perspective, and only general guidelines have been given.

2.2 Starting points of house fires

No official detailed statistics are published in UAE on the causes or starting points of house fires. Moreover, no published study could be found in the scientific literature that specifically discussed places where house fires start in UAE or in countries of a similar culture. To overcome this shortage of studies, a short questionnaire was developed and distributed randomly to a sample of house occupants in UAE who had experienced accidental fire in their houses with the aim of determining where and how fires start in houses. More than one thousand randomly selected residents were approached in this regard. The purpose of the study was explained to them in brief and they were asked if they had experienced a (detached) house fire in the last ten years and if they were willing to participate in this study. Only 104 of those approached had experienced a house fire in the past 10 years and were willing to respond to the questionnaire. The questionnaire asked seven questions as follows:

1. year of residential fire (or last fire if more than one);
2. gender of respondent;
3. type of residence (single- or double-storey);
4. number of people living with the respondent;
5. fire starting point (FGR, MGR, bedroom, GBR, family room, maid’s room, kitchen, storage room, toilets or other); and
6. cause of fire (ignition/flame/heat source, gas leak, frying/cooking, children playing, steamer/fumigator, cigarette butt, electrical short circuit or other).

2.3 Expert opinion

In developing most MCDM models, the number of experts whose opinion is sought depends on the scarcity of those experts. In many instances, the number ranges between one and nine (Al Hawarneh et al., 2019; Cheaitou et al., 2018; Li et al., 2015; Lima et al., 2014). In this part of the developed MCDM model, the opinion of eight experts was sought on the desired proximity of function areas at the design stage of detached houses. Each one of those experts had a minimum of five years’ experience in designing detached houses in UAE.

The experts were interviewed face-to-face where the detailed aim of the project was explained to them first. They were then asked to give their opinion on the desired relative proximity (i.e. degree of closeness) among the different house function areas in a way that would minimise fire risk and improve residents’ chances of surviving any residential fire, while taking practical requirements into consideration. This is done by asking them to rate the desired proximity of each pair of function areas on a relationship chart shown in Table II. These ratings, also given in Table III, range in value from 1 (equivalent to least desired proximity) to 3 (highest desired proximity) based on widely used facilities planning methodology described in Freivalds (2014). The meaning of these proximity ratings are illustrated in an example shown in Figure 1.

2.4 Application of the developed framework on existing house designs

The developed fire risk evaluation framework was then applied to a selected sample of ten detached house designs from Sheikh Zayed Housing Program Services (SZHP) and
Mohammed Bin Rashid Housing Establishment Services (MBRHE). The announced aim of the former housing program is to provide decent housing for all UAE citizens and improve their lifestyle. SZHP was established in 1999 and gave residential support to about 53,028 citizens across the country worth more than 22 billion dirhams in loans and grants. This residential support varied between construction of new homes, completion of semi-constructed houses, expansion of existing houses or maintenance of houses (Sheikh Zayed Housing Programme, 2015; The Emirates Centre for Strategic Studies and Research, 2012).

MBRHE was established in Dubai in 2006 to help provide adequate housing for its citizens. The number of loan applications submitted to MBRHE until 2011 reached 22,935 while approval was granted to 13,247 applications (The Emirates Centre for Strategic Studies and Research, 2012; Government of Dubai, 2015). Both housing programs provide applicants with ready-made and publicly available designs for houses and ten of these designs are evaluated in this study using the developed framework.

<table>
<thead>
<tr>
<th>Function area</th>
<th>FGR</th>
<th>MGR</th>
<th>Bedroom</th>
<th>GBR</th>
<th>Family room</th>
<th>Maid's room</th>
<th>Kitchen</th>
<th>Storage</th>
<th>Bath</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGR</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MGR</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bedroom</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GBR</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Family room</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maid's room</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kitchen</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
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</tr>
<tr>
<td>Storage</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bath</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Table II: Function areas relationship chart.

<table>
<thead>
<tr>
<th>Value</th>
<th>Rating</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>High desired proximity</td>
<td>Attached</td>
</tr>
<tr>
<td>2</td>
<td>Ordinary proximity</td>
<td>Nearby</td>
</tr>
<tr>
<td>1</td>
<td>Low desired proximity</td>
<td>Far</td>
</tr>
</tbody>
</table>

Table III: Proximity relationships.

Figure 1. An illustrative example of proximity rates.

Notes: Proximity rate (A, H) = 1; proximity rate (B, E) = 2; proximity rate (A, C) = 3
3. Results

3.1 General design guidelines from the literature

Based on the literature review presented earlier and the UAE Fire and Life Safety Code of Practice (Ministry of Interior, 2011), three general guidelines for designing houses from a fire safety perspective could be developed as follows:

(1) There should be two or more exits in any house spread over two or more sides of the house. These exits should be close to the middle of the side of the house to make them as accessible as possible to house occupants in all function areas.

(2) Store rooms should be located away from escape routes and exits.

(3) Exits should be as close as possible to function areas that are the most likely starting points of house fires.

3.2 Expert opinion

Eight architects with at least five years’ experience in designing detached houses in UAE were invited to participate in this study and rate the relative degree of proximity among the different function areas in a typical UAE house. More specifically, they were asked to rate the desired closeness of each pair of function areas so that fire risk would be minimised while keeping practical requirements in consideration. A summary of the mode of their ratings of desired proximity of function areas is given in Table IV.

Discussion with house design experts also highlighted the urgency of increasing fire safety awareness among architects when designing houses because this matter is not fully taken into consideration at the design stage as it should be.

3.3 Survey results

Demographic characteristics of the 104 residents who responded to the questionnaire are given in Table V. As can be seen in this table, 60 per cent of respondents were females and

<table>
<thead>
<tr>
<th>Function area</th>
<th>FGR</th>
<th>MGR</th>
<th>Bedroom</th>
<th>GBR</th>
<th>Family room</th>
<th>Maid’s room</th>
<th>Kitchen</th>
<th>Storage</th>
<th>Bath</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGR</td>
<td>X</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>MGR</td>
<td>X</td>
<td>X</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Bedroom</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>GBR</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Family room</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Maid’s room</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Kitchen</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Bath</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Table IV. Function areas relationship chart based on expert opinion

<table>
<thead>
<tr>
<th>Gender</th>
<th>Male 40%</th>
<th>Female 60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>House type</td>
<td>Single-storey 39%</td>
<td>Double-storey 61%</td>
</tr>
<tr>
<td>No. of occupants</td>
<td>0-3 persons 31.70%</td>
<td>4-6 persons 38.60%</td>
</tr>
</tbody>
</table>

Table V. Demographic characteristics of questionnaire respondents
61 per cent live in double-storey houses. Also, the reported number of people living in respondents’ houses was spread among all three groups (0-3, 4-6 and 7 or more).

Questionnaire results show that the causes of detached house fires were electrical short circuit (21 per cent), frying/cooking (14 per cent), gas leak (14 per cent), ignition/flame/heat source (12 per cent), steamer/fumigator (11 per cent), candles (11 per cent), cigarette butts (5 per cent), children playing (2 per cent) and others (9 per cent). The function area within the house where the highest percentage of fires started was the kitchen with 36 per cent of all fires starting there. This was followed by living room (17 per cent), storage room (15 per cent), bathroom (11 per cent), maid’s room (8 per cent) and others (13 per cent). Based on these results, the following house design guidelines were added to the ones previously mentioned in the literature:

- Houses should be designed so that kitchens and living rooms should have more than one door.
- Kitchens and living rooms should not be the only escape route from other function areas (i.e. function areas adjacent to kitchens and living rooms should have other doors leading to other sides of the house).

4. Proposed framework
The framework that this study proposes to use to evaluate fire risk of detached house designs in the UAE and countries of similar cultural background includes three indicators. The first addresses whether a house design adheres (or not) to the five guidelines mentioned earlier. The second focuses on proximity levels, while the third indicator focuses on calculating fire risk scores. In terms of the second indicator, the differences between the desired relationship and the actual relationship were calculated as such:

\[ D_{ij} = |X_{ij} - Y_{ij}| \]

where \( D_{ij} \) is the difference between the desired proximity relationship \( X_{ij} \) and the actual proximity relationship \( Y_{ij} \) between function area \( i \) and function area \( j \).

The decision on this proximity level is suggested to be as follows:
- If \( D_{ij} \leq 1 \), the proximity between the two function areas is acceptable.
- If \( D_{ij} = 2 \), the proximity is not acceptable in terms of fire safety.

However, the third indicator, which focuses on calculating a fire risk score (FRS), is calculated using the following suggested formula:

\[ FRS = \sum_{i=1}^{9} \sum_{j=2}^{9} |(X_{ij} - Y_{ij})|, j > i \]

where \( X_{ij} \) is the desired relationship between function area \( i \) and function area \( j \) in the house design and \( Y_{ij} \) is the actual relationship between function area \( i \) and function area \( j \). It is worth mentioning that the score is the result of 36 summations.

To evaluate any house design, the following mechanism is suggested:
- If \( FRS \leq 10 \), general fire safety guidelines are satisfied and no cells with \( D_{ij} = 2 \): The design is safe.
- If \( 11 \leq FRS \leq 15 \), a maximum of one of the general fire safety guidelines is not satisfied, or one cell with \( D_{ij} = 2 \): The design is fairly safe but needs improvement to address minor violations.
5. Application of the proposed framework on a sample of house designs
After developing the guidelines, they were applied to ten semi-randomly selected and publicly available house designs. Five of these were house designs introduced by SZHP and another five by MRHE. Information on the ten selected house designs (MRHE, 2015; SZHP, 2015) as well as results of framework application on these designs are given in Table VI.

To illustrate how these results were obtained, a detailed evaluation of one of the ten house designs, Yaqoot-7, is undertaken. The Yaqoot-7 house design is a one-floor house. It has a built-up area of 2,238 square feet and comprises three bedrooms and four bathrooms (SZHP, 2015). The floor plan is shown in Table VII while actual proximity ratings chart is shown in Table VIII. The difference between the desired proximity ratings chart and the actual proximity ratings chart is shown in Figure 2.

As can be seen in Tables VII, VIII and Figure 2, evaluation based on the proposed framework of the Yaqoot-7 house design shows that this design satisfies all general fire safety recommendations (i.e. it has a fire safety score of five and has no cells with $D_{ij} = 2$). It is, therefore, reasonable to conclude that this house design is satisfactory from a fire safety perspective. Table VI shows the outcome of the same analytical procedure after applying it to the other nine house designs. Such results suggest that this framework is practical and potentially applicable in real-life situations.

6. Framework validation
The proposed framework was then validated on five major detached house fires that occurred between March 2016 and November 2018. The aim was to apply the proposed framework on the design of those five houses to see if the designs violated the framework or not. Each of those incidents led to the fire spreading to several function areas of the house, enormous financial loss and, in three cases, loss of human life. Incomplete details of the fires were solicited from Sharjah Police Department without disclosing any personal details or addresses of anyone involved in the fires for legal reasons. A summary of this comparison is given in Table IX. It should be noted that FRS values reported in that table are rough estimates as not all house design details could be obtained.

As can be seen in Table IX, applying the proposed framework on the five house designs led to the conclusion that four of the designs did not comply with the proposed framework, while the design of the second house in the table was found to be fairly safe but needed some modifications. These results suggest that the framework is a good indicator for fire risk in house designs and can be implemented when designing detached houses alongside other measures such as mandatory installation of smoke detectors and fire extinguishers.

7. Conclusions
The aim of the study has been to develop a practical MCDM framework that can be employed to evaluate fire risks associated with detached house designs in UAE and in countries of similar cultural background. This study has been driven by a number of factors, including observed paucity of literature addressing fire safety at the design stage of detached houses. It is anticipated that this work will initiate and encourage more research in this area.
<table>
<thead>
<tr>
<th>Programme</th>
<th>House code</th>
<th>Area (sq.ft)</th>
<th>Levels</th>
<th>Satisfies recommendations</th>
<th>Score</th>
<th>Cells with $D_{ij} = 2$</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>SZHP</td>
<td>Alzumurd-4</td>
<td>3444</td>
<td>2</td>
<td>Yes</td>
<td>5</td>
<td>0</td>
<td>Safe design</td>
</tr>
<tr>
<td></td>
<td>Alzumurd-3</td>
<td>3692</td>
<td>2</td>
<td>Yes</td>
<td>19</td>
<td>3</td>
<td>Major design changes recommended</td>
</tr>
<tr>
<td></td>
<td>Almas-1</td>
<td>4908</td>
<td>2</td>
<td>Yes</td>
<td>9</td>
<td>1</td>
<td>Design improvements recommended</td>
</tr>
<tr>
<td></td>
<td>Yaqoot-7</td>
<td>2238</td>
<td>1</td>
<td>Yes</td>
<td>6</td>
<td>0</td>
<td>Safe design</td>
</tr>
<tr>
<td></td>
<td>Zafeer-4</td>
<td>2013</td>
<td>1</td>
<td>Yes</td>
<td>8</td>
<td>0</td>
<td>Safe design</td>
</tr>
<tr>
<td></td>
<td>House-2</td>
<td>3192</td>
<td>1</td>
<td>Yes</td>
<td>7</td>
<td>0</td>
<td>Safe design</td>
</tr>
<tr>
<td></td>
<td>House-6</td>
<td>3404</td>
<td>2</td>
<td>Yes</td>
<td>4</td>
<td>0</td>
<td>Safe design</td>
</tr>
<tr>
<td></td>
<td>House-11</td>
<td>4343</td>
<td>2</td>
<td>Yes</td>
<td>16</td>
<td>2</td>
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</tr>
<tr>
<td>MBRHE</td>
<td>House-12</td>
<td>4303</td>
<td>2</td>
<td>Yes</td>
<td>13</td>
<td>0</td>
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</tr>
<tr>
<td></td>
<td>House-14</td>
<td>4462</td>
<td>2</td>
<td>No</td>
<td>13</td>
<td>0</td>
<td>Major design changes recommended</td>
</tr>
</tbody>
</table>
The emergent MCDM framework has been developed from the literature, expert opinion and an assessment of fire start areas. The framework was tested for validity against ten existing house designs and against five detached house fires in UAE. Outcomes of the tests suggest practical benefits from the emergent framework. Thus, it can be argued that the proposed framework has practical fire risk minimisation benefits for house designers and architects.

<table>
<thead>
<tr>
<th>Function area</th>
<th>FGR</th>
<th>MGR</th>
<th>Bedroom</th>
<th>GBR</th>
<th>Family room</th>
<th>Maid’s room</th>
<th>Kitchen</th>
<th>Storage</th>
<th>Bath</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGR</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MGR</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Bedroom</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>GBR</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Family room</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Maid’s room</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Kitchen</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Bath</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table VII. Actual function areas relationship chart of Yaqoot 7 house design

<table>
<thead>
<tr>
<th>Function area</th>
<th>FGR</th>
<th>MGR</th>
<th>Bedroom</th>
<th>GBR</th>
<th>Family room</th>
<th>Maid’s room</th>
<th>Kitchen</th>
<th>Storage</th>
<th>Bath</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGR</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MGR</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>–1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bedroom</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>–1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>GBR</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Family room</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>–1</td>
<td>0</td>
<td>–1</td>
</tr>
<tr>
<td>Maid’s room</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>–1</td>
<td>0</td>
<td>–1</td>
</tr>
<tr>
<td>Kitchen</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Storage</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
</tr>
<tr>
<td>Bath</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table VIII. Difference between actual and desired function area relationship charts of Yaqoot-7 house design

Figure 2. Ground floor plan for Yaqoot 7 house (taken from SZHP, 2015)
Table IX. Valuating the developed framework on five major house fires

<table>
<thead>
<tr>
<th>No.</th>
<th>Fire details</th>
<th>1st indicator (design guidelines)</th>
<th>2nd indicator (proximity)</th>
<th>3rd indicator (FRS)</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fire started in storage room which is attached to family room and very close to the main entrance. Most of the single-storey house was destroyed and two children died</td>
<td>Guidelines 2 and 5 were violated</td>
<td>D_{storage-family} = 2 and D_{kitchen-storage} = 2 (all other D values are less than or equal to 1)</td>
<td>FRS = 17</td>
<td>House design is not safe in terms of fire risk according to the proposed framework</td>
</tr>
<tr>
<td>2</td>
<td>Fire started in main bedroom which is attached to family room and very close to the main entrance. Most of the single-storey house was destroyed</td>
<td>Guideline 5 was violated</td>
<td>All D values are less than or equal to 1</td>
<td>FRS = 11</td>
<td>House design is fairly safe in terms of fire risk according to the proposed framework but needs improvement to address minor violations</td>
</tr>
<tr>
<td>3</td>
<td>Fire started in MGR which is situated at the corner of the house and has the main entrance to the house. Most of the single-storey house was destroyed</td>
<td>Guidelines 1, 4 and 5 were violated</td>
<td>All D values are less than or equal to 1</td>
<td>FRS = 16</td>
<td>House design is not safe in terms of fire risk according to the proposed framework</td>
</tr>
<tr>
<td>4</td>
<td>Fire started in storage room which is attached to family room and very close to the front entrance. The whole single-storey house was destroyed and two people died</td>
<td>Guidelines 2, 4 and 5 were violated</td>
<td>D_{storage-family} = 2 and D_{kitchen-storage} = 2 (all other D values are less than or equal to 1)</td>
<td>FRS = 13</td>
<td>House design is not safe in terms of fire risk according to the proposed framework</td>
</tr>
<tr>
<td>5</td>
<td>Fire started in family room which has the only entrance to the double-storey house. The whole house was destroyed with multiple fatalities</td>
<td>Guidelines 1, 3, 4 and 5 were violated</td>
<td>D_{storage-family} = 2 and D_{kitchen-family} = 2 (all other D values are less than or equal to 1)</td>
<td>FRS = 20</td>
<td>House design is not safe in terms of fire risk according to the proposed framework</td>
</tr>
</tbody>
</table>
8. Limitations
As expected, the study does have some discernible limitations. One such limitation is that because of the restricted parameters that were incorporated into framework development, the emergent framework can be applied only to houses of certain design characteristics in terms of area and culture. This framework might not be applicable to houses of different scope as they would have different function areas. The second limitation of the study relates to a lack of detailed and comprehensive data on starting points of house fires within the UAE. Availability of such data would have been beneficial in broadening the validation process of the proposed model.

References


Ragette, F. (2001), *Traditional Architecture of the Arab Region and the Impact of the West*, Department of Architecture, American University of Sharjah, Sharjah, UAE.


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Abstract

Purpose – In their delivery of service, quantity surveyors are not in any way protected against threats and changes in their operating environment as a result of globalisation and continuous change in demand of clients. This research therefore examined the current and important areas of competencies of Nigerian quantity surveyors in their quest to continue to provide value for money for their clients.

Design/methodology/approach – Primary data were collected through administration of questionnaires on quantity surveyors that are members of the Nigerian Institute of Quantity Surveyors (NIQS). Mean item score (MIS) was used to rank required and exhibited competencies while gap and quadrant analyses were employed to evaluate their importance and proficiency level.

Findings – Core competencies required of quantity surveyors are costing of construction works; valuation; estimating and tendering; and procurement management while valuation; estimating and tendering; and costing of construction works are top three competencies currently exhibited. There is significant difference in the level of importance of the competencies areas compared to their exhibition by quantity surveyors.

Originality/value – It was noted that some important areas of competencies are not currently exhibited by quantity surveyors in the study area, there is therefore the need for personal and collective continuous development through workshops, conferences and seminars that will enhance the identified competencies areas. Training of undergraduates and retraining of practicing quantity surveyors is also essential to inculcate competencies that are not currently exhibited. This will benefit quantity surveyors and bodies concerned with the regulation of the profession in their quest for better service delivery.

Keywords Competencies, Human resources management, Training, Quadrant analysis, Gap analysis, Quantity surveyor, Skills

1. Introduction

Acquiring the core competencies contingent for personal, business and organisational improvement has been documented as a fundamental premise for engendering professional development (Ahadzie et al., 2009). Owing to this, Abraham et al. (2001) noted that competency-based measures have become an important alternative for identifying and developing realistic and practical training requirements, especially as the measures reflect a cyclical and continuous process of evaluating, planning and taking corrective action where necessary.

Quantity surveyors are one of the key professionals in the construction industry; they are trained to regulate and manage construction projects through feasibility studies, project procurement, contract administration, cost planning, cost management and asset financial management (Wao, 2016). In South Africa, Nkado (2000) and Nkado and Terry (2001)
assessed the importance of competencies that were essential for excellence in the current and future quantity surveying services. The study also evaluated the difference between important competencies and their current usage level by professional quantity surveyors. It was concluded that management-orientated competencies, which will eventually become important for the future business success of quantity surveyors, should be included in the academic and training curricula of quantity surveyors.

Crafford and Smallwood (2007) assessed quantity surveyors’ competence based on the perception of client; the findings were in tandem with Nkado (2000). Said et al. (2010) examined the importance of professional competence with respect to issues relating to quantity surveyors’ competency in Malaysia. It was revealed that quantity-surveying educators and practices alike are still deeply entrenched in the traditional core competencies rather than the emerging, newer services and skills. In support of this assertion, Oke et al. (2018) noted that quantity surveyors are not engaged as procurement managers in Nigeria because of lack of competencies to function as such. Pearson, Fitzgerald and Walsh (2002) investigated the changing infrastructural and developmental needs of quantity surveyors in a post-recession industrial environment that satisfies the aspirations of industrial, professional and academic stakeholders. The study reviewed competencies and their application in the delivery of quantity-surveying programmes from the perception of industry and academia with a view to delivering framework for alignment-selected stakeholders.

The unique nature of the construction industry, coupled with the challenges of global competitiveness, demand for sustainable development and changing regulatory requirements, has resulted in innovativeness in the practice of construction professionals. Lam (2009) noted that professional services are heterogeneous, intangible and multi-dimensional. It is therefore crucial to ensure that performance quality is accurately measured and assessed. One way of updating a profession’s knowledge base is to ensure that the constituent skills, abilities and value of the profession are subjected to constant and continuous evaluation to critically highlight the important competencies (Dada and Jagboro, 2012; Wao, 2016; Ogunsina et al., 2018). In view of this, this study evaluates the currently exhibited and required competencies of quantity surveyors with a view to enhancing their quality of services, remaining in business and continuing to compete effectively and adequately.

2. Literature review
2.1 Concept of competency

The issue of workers’ competencies had been discussed by industrialists, management practitioners, academics and other stakeholders since the 1960s (Kak and Sushil, 2002). It was however noted that the thinking on competencies and corporate strategy remained dormant during the 1970s and early 1980s. This is associated with the fact that management practitioners and academics paid more attention to other approaches of strategy than the earlier ones. In the late 1990s, the idea of competence had gained greater credence and was widely used in nearly all industries around the world. Rankin (2000) reported that a significant number of companies in the UK were using competencies to improve individual and their corporate performance. Baker et al. (1997) observed that companies were starting to look into workers’ competencies when it was realised that providing a framework that brings greater clarity to the idea of competence in business, operations and technology management would bring competitive advantage to their organisations.

Competence is related to an aspect of a job that an employee can perform. It is the demonstration of an integration of knowledge, training, skills, personal attributes and value orientation of an individual. According to Pearson et al. (2002), competency is concerned with the knowledge, skills and qualities of an effective manager and points to the ability to
perform the functions associated with management effectively in the work situation. Competency has been linked with behaviour and job performance of individual. According to the Royal Institute of Chartered Surveyors (RICS), competency is the knowledge, skills, training, abilities and behaviours needed for a particular role or task (RICS, 2014). It is the state or quality of being adequately qualified and the ability to perform a specific role (Chan et al., 2013). More so, Koustelios (2003) defined competency as having the capability, as well as possessing certain skills and required knowledge, to do what one is supposed to do. Fullerton et al. (2003) noted that competency describes a comprehensive profile of the knowledge, skills and professional behaviours that can be expected for a particular professional group. In summary, competencies are specific knowledge, skills, training, attributes, abilities, characteristics and behaviours that enhance job performance of an individual. It is the underlying characteristics that enable a person to demonstrate effective and efficient performance in a job.

A review of the related literature reveals that ideas and thinking surrounding the notion of competence is far from uniform and that the term has different meanings in different contexts. There are a number of general approaches to defining competence. They include performance in diverse settings and achievement of outcomes and specific skills and standard. The concept of competency has been approached in a number of ways, which include a set of behaviour patterns, high performance competencies, interpretative approach to competencies, a process of learning and a time-based approach to competencies. In the context of this study, competence will be regarded as the skill and ability of a person to effectively perform and cope with job demands of a workplace in relation to occupational competencies.

2.2 Quantity surveyors’ competence requirement framework
Quantity surveyors are professionals trained, qualified and recognised to provide cost advice for infrastructural projects. These include cost planning, procurement advice, contract administration, and settlement of contractual claims; however, Ashworth et al. (2013) concluded, the role of quantity surveyors has evolved and emerged to become more proactive than reactive in providing better value of services to meet their clients’ changing demands. A competent quantity surveyor must have a range of skills, training, knowledge and understanding which can be applied in a range of circumstances and organisation (Hassal et al., 1996). Therefore, a performance indicator is required for quantity surveyors to realise what they have to obtain to provide the service that meets their clients’ needs.

Oke and Ayodele (2019) noted that major challenges facing quantity surveying curriculum for construction industry practice in Nigeria are related to readiness of quantity surveyors to embrace changes and innovative practices in the construction industry. Over the years, the RICS has continuously sets out the requirements and competencies for the assessment of professional competence. These competencies are not just a list of tasks or functions but are also based on attitudes and behaviours studied over a period of time. The competencies are drawn in a generic way so that they can be applied to different areas of practice and geographical locations (RICS, 2014). These areas of competencies were adopted for the study. The competencies indicated in Table I are defined at three major levels of attainment, and each assessment of professional competency pathway has its specific combination of competencies that must be achieved at the appropriate level. The competencies are in three distinct categories, that is, mandatory, core and optional. Mandatory competencies are related to the personal, interpersonal, professional practice and business competencies; core competencies are fundamental competencies required for every quantity surveyor in the assessment of professional competence; while optional
competencies are a set of competencies selected by individual quantity surveyors from a list defined for the particular pathway. These are mostly technical competencies.

The Australian Institute of Quantity Surveyors (AIQS) also develop a model of competencies for the Australian quantity surveyors (AIQS, 2012). A total of 31 competency standards that need to be adhered to by the professional body in producing competent quantity surveyors were proposed. These competencies were subdivided into four headings, which include project cost management competencies, asset financial management competencies, specialised management competencies and support competencies. The Pacific Association of Quantity Surveyors analysed a full range of competencies required by a modern quantity surveyor. In principle, the body agreed to accept ten competency standards for their quantity surveyors (PAQS, 1999): strategic planning, budgetary process, cost estimating, cost planning, procurement advice, documentation, tendering process, construction account management, construction change management and feasibility studies. For this study, RICS list of competencies were adopted because of the affiliation of NIQS to the body. More so, Nigeria is a member of the Commonwealth Countries, with a British linkage.

3. Research methodology

Using survey design, primary data were collected through quantitative approach for the study. The population comprised quantity surveyors who were registered to practice by the Nigerian Institute of Quantity Surveyors (NIQS) in Lagos state, Nigeria. Lagos state was selected due to high number of construction professionals as well as recognised procurement officers by the government of the state. In the selected study area, there are 141 record of these professionals. Respondents were divided into various groups based on their type of...
organisation. These include consulting, contracting, private (such as banks, insurance companies, housing companies, etc.) and government agencies and establishments (at federal, state and local government level, including lecturers and quantity surveyors attached to works departments in higher institution). In sampling of the respondents, census probabilistic sampling method was used because of the manageable size of the population, and closed-ended questionnaires were adopted in the collection of data. The instrument was prepared in English because it is the official language of the country of study and because it was expected that the quantity surveyors, by their virtue of training and experience, possessed the required knowledge of the language to respond accordingly. In preparing the questionnaire, a cover letter was provided to intimate respondents on the purpose of the study and choice of respondents to participate in the study.

To eliminate bias, no form of incentive was provided and respondents were given ample time to complete the instrument. For ethical consideration, information was provided, in the cover letter, that data supplied by respondents will be solely used for academic purpose. More so, questions that could reveal the identity of the respondents were avoided and it took an average of 8 min to complete one questionnaire. Majority of the questionnaires were self-administered on the respondents while others were through the use of electronic-mail system. The first part of the instrument solicits information on general characteristics of respondents, while the second part was structured to seek information regarding required and exhibited areas of competencies of quantity surveyors using a five-point Likert scale.

Information regarding the demographic details of respondents was analysed using frequency, percentile and average mean. For the main section, the adopted Likert scale was used to obtain mean item score (MIS) and significance values for each of the identified variables. The MIS was further used to rank the importance of exhibited and required competencies of quantity surveyors. It was also the basis for the computation of gap and quadrant analysis. ANOVA test was used to generate F-ratio and significance value so as to examine the degree of discrepancies of identified groups of respondents with respect to each of the variables.

Gap analysis is concerned with the comparison of the actual importance and required or desired performance (Vrolijk and Hepworth, 2015). This was used in this study to calculate and compare the difference in the mean of exhibited and required areas of competencies of quantity surveyors. Quadrant analysis was further used to identify and assess the variables. According to Benjamin (2014), a quadrant plot, which is the basis of quadrant analysis, is a measure of importance vs performance and usually shows key areas for improvement. An importance-exhibited quadrant analysis was carried out to integrate the rankings of current importance and exhibited levels of areas of competencies of quantity surveyors to identify areas for improvement and further development.

Prior to the study, a pilot study was conducted to verify the instrument for data collection. Four professional quantity surveyors, two PhD holders and three PhD students were involved in the study. Technical and grammatical errors were pointed out, and their suggestions, comments and observations were incorporated into the final instrument. Reliability test was computed to examine the reliability of the five-point Likert scale used for the study. Cronbach’s alpha (\(\alpha\)) values of 0.850 and 0.922 were obtained for required and exhibited sections, respectively. This indicates that the adopted instrument is reliable because the values tend towards 1.00 than 0.00. Moser and Kalton (1999) noted that degree of reliability of an instrument is perfect, as the value tends towards 1.00, while Doloji et al. (2010) suggested a cut-off value of 0.70.
4. Findings and discussion

From the administered 141 questionnaires, 118 were retrieved, but only 115 were found usable. The remaining three were not correctly filled and vital information was missing. All the respondents are members of NIQS with an average of nine years of experience. This indicates that this group of respondents has good and sufficient knowledge of their profession, thereby supplying credible information for the study. More so, respondents are spread across various identified groups, that is, consulting, contracting and private- and government-related establishments, with 51.30, 20.00, 10.44 and 18.26 per cent, respectively.

4.1 Required and exhibited competencies

In assessing areas of competencies required by quantity surveyors at present, Table II indicates the results from the survey. The first six required areas of competencies are the

<table>
<thead>
<tr>
<th>Quantity surveyors competencies</th>
<th>Required Mean</th>
<th>Rank</th>
<th>Exhibited Mean</th>
<th>Rank</th>
<th>Mean Gap Mean</th>
<th>Rank</th>
</tr>
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<td>Conflict avoidance, management and dispute resolution procedures</td>
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<td>3.51</td>
<td>26</td>
<td>0.75</td>
<td>1</td>
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<td>3.32</td>
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<td>3.27</td>
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<td>0.32</td>
<td>11</td>
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<td>3.32</td>
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<td>4.58</td>
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<td>18</td>
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<td>4.45</td>
<td>6</td>
<td>0.19</td>
<td>22</td>
</tr>
<tr>
<td>Construction technology</td>
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<td>4.33</td>
<td>8</td>
<td>0.16</td>
<td>23</td>
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<td>4.15</td>
<td>13</td>
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<td>23</td>
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<td>33</td>
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<td>26</td>
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<td>Estimating and tendering</td>
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<td>2</td>
<td>4.62</td>
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<td>28</td>
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<td>Accounting principles and procedure</td>
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<td>24</td>
<td>3.67</td>
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<td>3.99</td>
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<td>4.68</td>
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<td>0.04</td>
<td>31</td>
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<td>Contract practice</td>
<td>4.29</td>
<td>15</td>
<td>4.35</td>
<td>7</td>
<td>−0.06</td>
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<td>Project financial control and reporting</td>
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<td>4.31</td>
<td>9</td>
<td>−0.06</td>
<td>32</td>
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<td>Contract administration and documentation</td>
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<td>4</td>
<td>−0.14</td>
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<td>3.91</td>
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<tr>
<td>Client care</td>
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<td>24</td>
<td>4.01</td>
<td>16</td>
<td>−0.24</td>
<td>36</td>
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</tbody>
</table>

Table II. Mean and gap analysis of required and exhibited competencies

Average 4.12 3.88 0.24
costing of construction works, estimation and tendering, valuation, quantification of construction works, project management and cost planning. Others are conduct rules, ethics and professional practice; communication and negotiation; construction technology; and team working and data management. It was however observed that most of the required competencies were related to core and mandatory services; there was no optional service in the first ten. The least required competency area which is ebbed at the bottom is majorly the optional competencies. These include business planning, sustainability, environmental services, building information modelling (BIM) management, capital allowances, corporate recovery and insolvency and facility management. It was noted that sustainability, a core competency and one of the emerging trends in the world, is among the least required areas of competencies.

The required competencies were further subjected to ANOVA to determine if there was a significant difference in the mean score of various groups of respondents. The result of p-values in Table III revealed that there was no significant difference in mean values for competencies areas such as accounting principles and procedure, conflict avoidance, management and dispute resolution procedures, design economics, contract practice, contract administration and documentation, due diligence, insurance, programming and planning, valuation and value management. For the remaining competencies, there was a statistically significant difference in the mean values of both respondents.

Areas of competencies exhibited by quantity surveyors in the study area are indicated in Table II. The major areas are valuation; estimation and tendering; and costing of construction works, and these are primarily concerned with core areas of competencies. Other highly exhibited competencies are quantification of construction works; contract administration and documentation; cost planning; contract practice; construction technology; and project and financial control. Only one of the optional competencies, that is, contract administration and documentation, is among the first ten exhibited by the quantity surveyors. The least exhibited competencies areas are health and safety; business planning; environmental services; BIM management; capital allowances; corporate recovery and insolvency; and marketing.

ANOVA was used to generate F-ratio and significance value so as to examine the degree of discrepancies of various groups of respondents with respect to exhibited areas of competencies. In Table III, the analysis revealed that p-value of 25 out of the 36 factors is lower than 0.05. It can thus be concluded that there is significant variance among various categories of respondents in the mean values the identified 25 competencies areas.

4.2 Competencies gap analysis
To examine the gap between required and exhibited competencies of Nigerian quantity surveyors based on the respondents’ response, the Mann–Whitney U test was carried out. The analysis indicates a Z value of −0.676 and an asymptotic significance (two-tailed) value of 0.499. The asymptotic significance of 0.499, which is greater than 0.05, implies that there is no significant difference in the areas of competencies required and exhibited by Nigerian quantity surveyors. However, a negative Z-value indicate that the level of exhibition of some of the competencies is not directly proportional to their current level of requirement. This implies that the areas of less importance are currently exhibited by the professionals.

Furthermore, the gap analysis method was adopted to compare exhibited and required competency areas. Table II indicates the mean gaps amongst areas of competencies for quantity surveyors. The five competencies with the largest gap are conflict avoidance; management and dispute-resolution procedures (gap value of 0.75); data management (0.66); health and safety (0.49); and conduct rules, ethics and professional practice (0.57), which are part of the mandatory competencies expected to be evident in a professional quantity
surveyor. This connotes that Nigerian quantity surveyors are not exhibiting most of these mandatory competencies as expected. There are negative values for client care; contract practice; project financial control and reporting; contract administration and documentation; and risk management. This indicates that quantity surveyors are exhibiting the skills than it is currently required.

4.3 Required-exhibited competencies quadrant analysis

Figure 1 presents the importance-evidence quadrant analysis plot. The y-axis represents the mean values of the exhibited competencies, while the x-axis represents the mean values of the required competencies. The plots are represented with the competencies code and mean

<table>
<thead>
<tr>
<th>Competencies</th>
<th>Exhibited F-ratio</th>
<th>Sig (p-value)</th>
<th>Required F-ratio</th>
<th>Sig (p-value)</th>
</tr>
</thead>
<tbody>
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<td>39.350</td>
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<td>Programming and planning</td>
<td>3.957</td>
<td>0.000**</td>
<td>29.146</td>
<td>0.506</td>
</tr>
<tr>
<td>Project evaluation</td>
<td>4.001</td>
<td>0.000**</td>
<td>39.283</td>
<td>0.020**</td>
</tr>
<tr>
<td>Risk management</td>
<td>1.048</td>
<td>0.002**</td>
<td>0.060</td>
<td>0.001**</td>
</tr>
<tr>
<td>Valuation</td>
<td>4.638</td>
<td>0.007**</td>
<td>1.889</td>
<td>0.442</td>
</tr>
<tr>
<td>Facility management</td>
<td>8.917</td>
<td>0.511</td>
<td>24.611</td>
<td>0.000**</td>
</tr>
<tr>
<td>Financial management</td>
<td>0.546</td>
<td>0.409</td>
<td>55.056</td>
<td>0.008**</td>
</tr>
<tr>
<td>Project Management</td>
<td>12.712</td>
<td>0.175</td>
<td>62.850</td>
<td>0.000**</td>
</tr>
<tr>
<td>Value Management</td>
<td>1.601</td>
<td>0.057</td>
<td>28.650</td>
<td>0.140</td>
</tr>
<tr>
<td>Marketing</td>
<td>14.018</td>
<td>0.000**</td>
<td>20.271</td>
<td>0.000**</td>
</tr>
</tbody>
</table>

Average 4.12

Note: **Difference significant at p < 0.05
values listed in Table II. The average mean of the level of importance and evidence of the competency areas are 4.12 and 3.88, respectively. All plots before mean 4.12 fall below average under the importance axis, while all plots before 3.88 on the evidence axis fall below average.

Based on variables plot in Figure 1, as well as average mean and rank of variables in Table II, Figure 2 indicates required-exhibited competencies quadrant analysis. Competencies shown in the lower right-hand quadrant are the competencies that require immediate attention for the profession to sustain its present relevance while those at the upper right-hand quadrant are competencies that needs continuous improvement through training. The figures in brackets are the required and exhibited rankings of variables.

Competencies shown at the lower left-hand quadrant are competencies that are below average in both importance and evidence and needs immediate action. The important-evidence quadrant analysis reveals the areas of competencies that requires immediate attention and this includes conflict avoidance, management and dispute resolution procedures, value management and data management. Areas such as sustainability, health and safety, business planning and accounting principles and procedures, which are part of the quantity surveyors’ mandatory competencies, are rated below average from both required and exhibited perspectives.
4.4 Discussion of findings

Three of the core competencies of quantity surveyors, namely, quantification and costing of construction works; estimating and tendering; and cost planning (RICS, 2014; Dada and Jagboro, 2018) are among the five most important competencies currently required of quantity surveyors in the study area. The outcome is in agreement with Nkado (2000) and Said et al. (2010). This is also supported by the findings of Dada and Jagboro (2012) that the listing of cost planning and control as the most important competencies may not be out of place because the basis of quantity surveyors’ duty lies in the financial and contractual control of construction project. A total of 20 competencies were rated above average and deemed important, while 16 were rated below average. Facility management, which was rated as part of the bottom four, is in agreement with Nkado and Terry (2001) where it was also rated as part of the bottom four competencies that are rated below average.

For competencies exhibited by quantity surveyors, 21 of the identified 36 were rated to be above average. The first five competencies are valuation; estimating and tendering; quantification and costing of construction works; contract administration and documentation; and cost planning and contract practice. This is supported by the finding of Nkado (2000), Oke and Ogunsemi (2009); and Sonson and Kulatunga (2014) in which measurement, valuation and construction contract practice were identified as important areas of competencies. In the gap analysis, there are negative values for client care; contract practice; project financial control and reporting; contract administration and documentation; and risk management indicating that quantity surveyors are exhibiting the skills than required in the current ways of discharging their duties. It is therefore necessary for quantity surveyors to redirect their skills and effort in these areas towards the more required competencies.
Importance (required)-evidence (exhibited) quadrant analysis helped to integrate the current important and evidence competencies and to highlight areas of immediate attention for continuous improvement through education and training. It was observed that competencies such as conflict avoidance, management and dispute procedures; data management; and value management are among the important competencies of immediate relevance. Competencies such as health and safety; business planning; accounting principles and procedure; and sustainability were below average both in importance and evidence rating. It is worth noting that these competencies are classified by RICS (2014) as mandatory competencies compulsory for all quantity surveyors. The low ratings could suggest that quantity surveyors’ services are not pronounced in these areas. It is also important to note that marketing was rated below average both in importance-evidence rating. Nkado (2000) noted that management-oriented competencies such as marketing will become more important for business success of quantity surveyors.

5. Conclusion and recommendation
The current most important competencies required of quantity surveyor are quantification and costing of construction works; valuation; estimating and tendering; cost planning; and project management. However, the competencies deployed with greatest proficiency among quantity surveyors in practice are: valuation; estimating and tendering; quantification and costing of construction works; contract administration and documentation; and cost planning. Areas of important competencies of immediate relevance are conflict avoidance, management and dispute procedures; data management; value management; client care; risk management; programming and planning, marketing; health and safety; accounting principles and procedure; business planning; corporate recovery and insolvency; BIM management; capital allowances; insurance; sustainability; design economics; and due diligence.

Some competency areas of quantity surveyors require improvement in current education and training of quantity surveyors are procurement management. These areas include project management; project evaluation; cost planning; commercial management of construction; estimating and tendering; quantification and costing of construction works; communication and negotiation; team working; professional practice; and construction technology. There is a need for continuous training and development of these competencies areas by academic institutions training quantity surveyors and the NIQS. NIQS and the Quantity Surveyors Registration Board of Nigeria should endeavour to make strong representation in the review of quantity surveying academic programme to reflect the important competencies which are lacking in the current programme. More so, quantity surveyors need to keep abreast with recent and emerging trends in the world through personal development, especially in the area of research, development and IT skills. This can be achieved through attendance and participation in seminars, workshops, symposium, conferences, etc., on relevant areas within and outside the country.

The study was limited to quantity surveyors practising in Lagos state, Nigeria, because of a recognised body of procurement officer by the state government. However, the quantity surveyors Registration Board of Nigeria and NIQS can take advantage of the findings of this study to develop future curriculum for the profession. More so, individual quantity surveyors, as well as firms and organisations with quantity surveyors, can make use of the findings of this study to identify their needed competence for future relevance.
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Further reading


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A framework integrating corporate social responsibility for marketing architectural design firms in developing countries

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Abstract
Purpose – This paper aims to develop a framework based on corporate social responsibility (CSR) as a novel approach for marketing architectural design firms (ADFs) in developing countries.

Design/methodology/approach – To achieve this aim, a research strategy consists of literature review and survey questionnaire is designed to accomplish four objectives: first, to examine the concepts of marketing and CSR in construction; second, to investigate the perception and application of CSR as a marketing tool for ADFs in developing countries; third, to develop a framework based on CSR as an approach for marketing ADFs in developing countries; and finally, to outline research conclusions and recommendations useful to government, ADFs and future research.

Findings – The research highlighted the inefficiency of current marketing strategies in developing countries due to lack of considering community needs, using incomprehensible technical language in communication with clients and misrepresenting the calibers of ADFs. ADFs believe that CSR can play a role in increasing their marketability. This requires governmental involvement and overcoming the barriers of adopting CSR.

Originality/value – This paper proposed a framework based on CSR as a novel approach for marketing ADFs in developing countries. This ideology has received scant attention in construction literature. The proposed framework represents a synthesis that is novel and creative in thought and adds value to the original body of knowledge in a manner that has not previously occurred.

Keywords Marketing, Corporate social responsibility, Developing countries, Egypt, Framework, Architectural design firms

Paper type Research paper

1. Introduction
About 85.4 per cent of the world population lives in developing countries. These countries are lands of contrasts. Despite the great mineral wealth, geographic locations, human resources, agricultural exports and reasonably sophisticated manufacturing and services sectors, the majority of the people are poor and large parts of the rural hinterland are underdeveloped and lacking in basic amenities such as clean water, health care, sanitation and electricity (Human Development Report, 2016; Zeybek and Kaynak, 2009; Cohen, 2006). Governments in developing countries are responsible for delivering projects and infrastructure facilities that help achieving the social and economic development objectives. Architectural design firms (ADFs) play a significant role toward supporting governmental authorities accomplishing these objectives through delivering infrastructural, industrial, educational, cultural, transportation, medical and residential projects that provide societies with their needs and fulfill their requirements (Othman, 2012; Khan, 2008; Mthalane et al., 2007; Field and Ofori, 1988). The increasing number of ADFs in developing countries...
resulted in a fierce competition between these firms to win new projects. This provided the client (e.g. public or private sector) with the opportunity to select the most appropriate ADF based on its resources, capabilities, problem-solving approaches and experiences. ADFs that fail to promote their products and services encounter the risk of losing their customers and competitiveness. Current marketing strategies are insufficient due to lack of considering community needs (Eruz, 2013), using technical language in communication, which is difficult to understand by clients (Mitrache, 2012) and misrepresenting the calibers of ADFs (Mitrache, 2012). ADFs that wish to remain in market and compete for the future have to adopt innovative marketing strategies. Although it is not well searched topic in construction literature, corporate social responsibility (CSR) is one of the promising tools for marketing ADFs (Othman and Hafez, 2016). CSR is the obligation of an organization to act in a way that respects the norms and cultures of each community (Maignan and Ferrell, 2004) and serves the interests of its stakeholders beyond profit seeking (Schermernhorn et al., 2005; McAllister, 2005; Carroll, 1993). This research proposed the use of CSR as a marketing tool for ADFs in developing countries because it focuses on enhancing the community and meeting their requirements, which is aligned with the architect’s role, especially in developing countries, while improving financial performance, increasing sales and market share (Kotler and Lee, 2005; Colmer, 2003). Accordingly, this paper aims to develop a framework based on CSR as a novel approach for marketing ADFs in developing countries. To achieve this aim, two approaches, namely, literature review and survey questionnaire are used to achieve four objectives:

(1) firstly, to build a comprehensive background about the research topic through examining the concepts of marketing and CSR. This objective was achieved through literature review;
(2) secondly, to investigate the perception and application of CSR as a novel approach for marketing ADFs in developing countries. This objective was achieved through presenting and analyzing the results of a survey questionnaire conducted with a representative sample of ADFs in Egypt;
(3) thirdly, to develop a framework based on CSR as an approach for marketing ADFs in developing countries; and
(4) finally, to outline research conclusions and recommendations useful to government, ADFs and future research.

2. Literature review

2.1 Marketing

2.1.1 Definition and importance. Marketing is the process of keeping a firm’s present clients happy and attracting new ones. It is the set of activities and processes adopted for creating, communicating, delivering and exchanging offers that have value for customers, clients, partners and society at large. There have been several definitions put forward for marketing. The definition that would be adopted for the purpose of this research is the one suggested by the Chartered Institute of Marketing (CIM), which defined marketing as the management process responsible for identifying, anticipating and satisfying customer requirements profitably (CIM, 2015). Marketing is the key for running successful business. Customers have to be identified and accepted as the focal point for all business activities and capturing their needs and wants should be the initial point for all main business decisions.
2.1.2 Marketing in architecture. According to the American Institute of Architects (AIA) in 1909, architects were not allowed to market themselves in any possible way; as they believe that this may lead to some poor quality work getting more recognition and acceptance for having better marketing skills only. However, in Europe, architects did not find the urge to publicize their work as their skills and quality of work were the main aspects in their recognition and not their marketing skills. Although architects were not used to believe that their provided services require marketing, and mistakenly considering themselves free from the pressures of market; including demand and supply. However, architecture is still a profession that should make profits at the end of the day (Epead and Othman, 2014). Although this was long time ago, some perceptions still remain in nowadays’ architectural culture. These perceptions are concerned with how architects perceive themselves and their jobs along with their clients and the perception of the relation between clients and architects. Mitrache (2012) stated that the confusion in the relationship between the architect and the client evolved from the question of whether architects should obey the clients’ orders or they should take the lead and impose their own vision. This issue has caused a great deal of indecisiveness, which made the compatibility between architecture and the marketing strategy a difficult one.

2.1.3 Why architectural design firms need marketing. ADFs are in need of marketing due to the following causes:

2.1.3.1 Inflexibility of architectural culture:

Mitrache (2012) claimed that although the Architectural Engineering Profession (AEP) looks adaptable to changes through their designing tools, styles and services provided, ADFs are very rigid structures deep down to their management core. This rigidity explains their inability to be updated with the marketing tools and needs of the community.

2.1.3.2 Expanding industry:

On the contrary to old beliefs, the demand of ADFs is increasing rapidly due to the escalating concern towards architecture in the media and in the educated segments of the society. This subsequently increases the competition between ADFs especially after increasing their numbers due to the fresh graduates’ urge to start their own businesses and the new technologies in the field (Epead and Othman, 2014).

2.1.3.3 Economic recession:

The world economy is not stable, and definitely the construction and architecture industries are amongst the main fields to be influenced by any recession as result of being affected by the availability of the constructing materials and their fluctuating prices. That was one of the main reasons why ADFs felt the need to use the marketing tools to add value to their business and provide them with what they need to be seen (Mitrache, 2012).

2.1.3.4 Keeping current clients and attracting new ones:

In addition to the increase in competition, new marketing strategies should be introduced to identify each firm uniquely and to attract new customers as well as maintain regular ones. Yisa and Edwards (2002) and Butković (2010) highlighted two studies conducted in the UK and Croatia to investigate the application of the marketing strategies in the construction industry. Results of the UK study showed that 87 per cent of the contributing companies had a marketing programme with plans to penetrate new markets as well as keeping existing ones. In addition, 36 per cent of these companies attracted more new customers than those without a marketing strategy. Results of the Croatian studies showed that 80 per cent of the contributing companies believe that in order for construction companies to be effective, they should have a clear business strategy in place. Moreover, 57 per cent believes that this strategy should include marketing
plans, 63 per cent admitted that construction companies do need marketing but 36.67 per cent only described their marketing strategies as enough. These results revealed that despite the importance of marketing for ADFs, some companies still neglect this aspect.

2.1.3.5 Promoting the identity of architectural design firms:

ADFs as service-providers define their marketing process into a set of activities with the aim of promoting their identity; which is one of the main functions of marketing. A study conducted by the AIA in 2003 stated that American ADFs spend around 6.5-8% of their budget on marketing, which is considered as an upgrade in the significance of marketing in ADFs. However, in developing countries like Romania ADFs choose one of their staff to do the marketing tasks, along with sales and other managerial tasks, without allocating enough budgets on the process (Mitrache, 2012).

2.1.4 Current marketing functions in architecture. Nickels (1990) classified the marketing functions as differentiation function, segmentation function, contractual function and communication function.

2.1.4.1 Differentiation function. This function aims at creating a sense of uniqueness to the service provided to be able to attract clients in a way that satisfies their needs and wants in the best form (Nickels, 1990). According to Mitrache (2012), ADFs still use the same traditional methods for the differentiation function, which depends mainly on the word of mouth and the reputation of the firm in the relevant social circles. However, this method has its downfalls; as it may not reveal the best qualities of the business and are quite slow in their spreading action, which jeopardizes the business’s future because of not attracting enough clients at the needed times to ensure the survival of the firm. Another method of differentiation is tackling new fields that competitors had not invaded yet; which reduces competition and provides a unique selling point for the firms (McAdams, 2013). New fields could be a new type of structural system, new building type or a new technology that facilitates the way tasks are performed such as building information modeling (BIM).

2.1.4.2 Market segmentation function. This function is concerned with determining the targeted audience for the marketing strategy to come up with the most suitable and appropriate one that satisfies the customer needs. Along with determining whether a single strategy will be used for all segments or each segment would have a customized strategy according to its requirements, this function aids at the evaluation of the satisfaction of each segment separately and the identification of their needs in a more specific way (Nickels, 1990). Moreover, the market segmentation function prepares ADFs to determine the needed skills for the upcoming projects; and whether the firm could afford hiring architects with the required skills and experience (McAdams, 2013).

2.1.4.3 The contractual function. This function aims at gathering different parties affected by the marketing strategy so that they come in contact with each other; to start communication between those who are about to exchange mutual benefits. Thus, customers are able to allocate the organization that best serves their requirements (Nickels, 1990). However, this rarely happens with ADFs as they subconsciously get involved with focusing on competing with their competitors and peers rather than targeting and getting in contact with the clients instead. However, this is due to the fact that architects’ lifestyle involves so much competition with their peers during their studying years (Mitrache, 2012).

2.1.4.4 Communication function This is the most important function in any marketing strategy, as it includes the interchange of different thoughts and concepts and building bridges between different parties; while receiving the feedback to be able to evaluate the whole marketing strategy (Nickels, 1990). Communication parties may be represented as the organization and its clients, to identify the customer needs and wants; or the organizations
and its employees to ensure the service provided matches the organizations’ standards. In addition, communicating with other businesses in AEP such as contractors or graphic designers is a must for networking; to increase the exposure and widening the referrals circle (Mitrache, 2012). Moreover, communication includes constant contact between ADFs and their clients, even after the project is completed. McAdams (2013) confirmed that the long-term relationship between the architect and the past clients act as a reminder for the client to mention the architect’s name more. The increasing number of mentioning past clients do enhances the word of mouth spreading; which widens the network of the architect. This contact could be in the form of updating the client with changes and innovations that could be added to existing projects or could be a friendly notification of the architect’s new projects.

2.1.4.5 The valuation function. This function includes the analysis conducted between what is gained and what is provided in the exchange process and whether the benefits are worth the cost. The cost is in the form of prices in most of the cases but not exclusive to money; cost could be time, effort, etc., (Nickels, 1990). The marketing functions determine how the marketing strategy could be applied in service providing businesses such as architecture; to ensure results that would satisfy both parties (Felton, 1990).

2.1.5 Limitations of the current marketing strategies in architecture. The current marketing strategies are characterized with some limitations as follows:

2.1.5.1 The increase in the clients’ awareness levels of social responsibility:

Clients are now highly aware of the consequences of their purchasing practices on the society and are causing massive changes in the customer expectations that businesses were previously considering (Hejase et al., 2017). The Global CSR Study (2013) confirmed the claim that consumers are not only expecting companies to act responsibly toward the society but also embracing the concept on their own personal responsibility as individuals of the community. This highlights a weakness point in any company that neither takes CSR seriously nor integrates its main concepts within their corporate strategy, including ADFs.

2.1.5.2 Neglecting community needs and imposing alien cultures on them:

The marketing strategies used in some countries (e.g. China) do not respond to public demands but they create demand for new alien products, through advertising and deceiving the mass public into believing that they actually need them, for the sole purpose of maximising profits which goes against sustainable concerns of a community (Eruz, 2013).

2.1.5.3 Using technical language in communication:

Usually, during the marketing process in ADFs, the language used is full of technical jargon that is not understandable by clients; leaving them distracted from the original message conveyed through the promotion. However, this should not be the case because after all any technical jargon could be simplified and decoded to be comprehensible to non-architects (Mitrache, 2012).

2.1.5.4 Architectural design firms misrepresenting themselves:

Some small to medium ADFs face this problem when designing their own marketing strategy, especially if they do not have marketing specialists and assign this task to one of the staff. The problem is that ADFs promote themselves for what potential they see in their skills, and not for the current or existing skills in their hands. This leads to either missing the opportunities of working on small profitable projects or lead the firm to be involved in large projects that exceed its capabilities which might eventually cause failure of this project and ruining the firm’s reputation (Mitrache, 2012).
2.2 Corporate social responsibility

2.2.1 Definition and background. CSR is a social commitment, which includes the organization's obligation to be productive and sustainable to the economy. It comprises the commitment to abide by the rules, norms and values of the community (Carroll, 1979 cited in Maigman and Ferrell, 2004). CSR is concerned with directing the organizational activities to serve the interests of stakeholders (Schermherhorn et al., 2005) and follow the ways that organizations adopt to generate profits and monitor their impact on the broader community (Bradshaw and Vogel, 1981). Currently, the CSR concept is integrated into all aspects of business operations, visions, missions and value statements of organizations worldwide. CSR reports usually go beyond profit maximization to include the company's responsibilities to a broad range of stakeholders including employees, customers, community and the environment (Ofori and Hinson, 2007). However, this obligation was criticized for lacking the precision needed to be used in the management of CSR (Maigman and Ferrell, 2004). This led to CSR being viewed as stakeholder obligation; because the corporate should not be held responsible for the whole community but should take into consideration the stakeholders' interests only, in the form of organizational stakeholders, community and media (Wood and Jones, 1995 cited in Maigman and Ferrell, 2004).

The concept of CSR has been developed over the years, from the classical “profit-centered model” to the modern “socially responsible model” (Carroll, 1999). The classical model states that the primary responsibility of managers and directors is to operate in the best interests of the shareholders who are essentially the true owners of the corporation (Friedman, 1962, cited in Ofori and Hinson, 2007). The classical model perceives that the corporate expenditure on social activities is a violation of management’s responsibility to shareholders at least to the extent that these expenditures do not lead to higher shareholder wealth. Alternatively, the socially responsible model advocated by (Abrams, 1954 cited in Ofori and Hinson, 2007) stated that a firm's management is responsible for maintaining an equitable and working balance among the claims of the various directly interested groups such as stockholders, employees, customers and the public at large.

2.2.2 Corporate social responsibility of architectural design firms. ADFs have a duty not only to the client but also to society and to the environment at large. Architects play a significant role in the social and economic development of countries. They are the first line of contact with clients in the construction industry. Hence, their role should not be confined to the technical activities, rather to cover other activities that extend their role to improve the sustainability of the built environment through producing buildings and facilities that save the environment, enhance society and prosper the economy (Othman, 2009).

2.2.2.1 The corporate social responsibility of architectural design firms toward the environment. The construction process represents a major contributor to climate change, resources depletion, pollution and energy consumption at both local and international levels (Ofori et al., 2000; Addis and Talbot, 2001), accordingly, integrating environmental requirements into the design decision-making process is essential for producing buildings that save the environment. The CSR of ADFs toward the environment can be identified as:

- raising the community awareness about the necessity of saving the environment and promoting the adoption and application of sustainability principles in architectural design;
- using durable, environment friendly, non-toxic, easy to maintain, energy efficient and recyclable construction materials and equipment to reduce the negative environmental impact of buildings;
• developing designs that respond positively to the different environmental effects, forces and unexpected events; and
• supporting ADFs and other construction professionals to taking their responsibilities within their supply chains (Othman, 2009).

2.2.2.2 The corporate social responsibility of architectural design firms toward the society. Architecture represents an integral part of human activities. It affects every day’s experiences and actions. ADFs are responsible for developing cities, towns, projects and infrastructure facilities that fulfill communities’ cultural, social and economic needs and meet their expectations. The CSR of ADFs can be identified as:

• raising the community awareness regarding the important role that ADFs can play toward society development;
• identifying community requirements and engaging them in the design process to ensure that the developed projects meet their needs, fulfill their requirements and reduce the cost and implications of later modifications;
• providing buildings with health and safety requirements and equipment that facilitate the use of people with special needs;
• conducting post occupancy evaluation to get feedback from end-users to improve the performance of projects, increase their sustainability and achieve customer satisfaction (Othman and Elsaay, 2018);
• integrating CSR in the architectural engineering education programs and providing expert advice to non-experts through offering volunteer services.
• encouraging positive partnerships between the public sector and ADFs to support government initiatives toward achieving sustainable development objectives, improving collaboration and experience exchanges; and
• offering training programs and jobs for recently graduated architects and engineers and sponsoring students (Othman, 2009).

2.2.2.3 The corporate social responsibility of architectural design firms toward the economy. The economic dimension of sustainable architecture can be seen from two perspectives. First, stimulating growth in the construction industry, which increases the percentage of GDP and provides more job opportunities. Second, increasing clients’ profit and investment returns. The CSR of ADFs towards the economy can be identified as:

• highlighting the importance of the role that ADFs can play to improve the economy;
• ensuring that society’s funds and resources are used sparingly.
• promoting and supporting purchasing from supply chains that are committed to sustainability requirements in their products.
• considering the life cycle cost of the project and minimizing the cost of operation and maintenance.
• creating innovative ideas and using sustainable materials and technology, which can perform the same function or even better at lower cost;
• specifying locally manufactured materials to encourage the national economy and reduce the cost of importing materials; and
• using demolition materials in manufacturing new construction materials.
2.3 Creating job opportunities to reduce the unemployment rate and enhance families’ economic status (Othman, 2009) review of previous studies

The results of two recent studies conducted by Hafez and Othman (2016, 2017) were reviewed as they are closely linked to the scope of this research. The first study highlighted the inefficiency of current marketing strategies in developing countries due to the rise of clients’ awareness of social responsibility activities and their significance in maintaining sustainable communities. In addition, applying CSR concepts as a marketing strategy and respecting people’s needs and cultures increases projects success and the competitiveness of ADFs and ensures user satisfaction. This study depended mainly on reviewing and analyzing previous studies prepared in the fields of marketing, architecture and CSR and their relationship with each other. The second study investigated the role of community participation as a novel marketing strategy for ADFs in developing countries from a CSR perspective. The study revealed that architects lack of awareness about their firms’ strategies and visions highlight an obstacle in integrating CSR as a marketing strategy for ADFs. Although, architects believe in the importance of CSR in creating a successful business image, they also know that the clients’ current awareness levels in Egypt as a developing country might jeopardize the success of this image; as the clients might be more interested in lower prices rather than social responsibility. ADFs are aware of the CSR aspects. However, they believe that they need to understand how to apply these aspects in real life projects. The current marketing strategies for start-up ADFs depended heavily on the word-of-mouth and the appearance in exhibitions, which still proved insufficient to provide them with the needed publicity. Managers of ADFs believe that for the CSR to be integrated in the marketing strategies of ADFs, governmental plans involvement is necessary.

2.4 The relationship between corporate social responsibility, marketing and architectural design firms

Maignan and Ferrell (2004) stated that literature review does not contribute much to the integration of marketing and the socially responsible acts within the organization. However, Andreasen (1994) highlighted the emergence of the social marketing concept and the significance of integrating the marketing activities along with the socially responsible goals. The CSR concept could be well-integrated into the activities carried out in ADFs. The possibility of integration has to be examined through a small project and then evaluated by the architect to assess its effeffeness. As an example, Diebedo Francis Kere is an architect, who lives in Gando, Burkina Faso. The village of Gando has no electricity, no access to clear drinking water and no schools. He strived to provide an opportunity for all children in Gando to get an education and have better living conditions. The architect used clay to build some of the structures in the village, with the help of the entire community. The main aim of integrating the community was to train and teach them how to build similar structures without his help and to create a sense of belonging and commitment to preserve these buildings as they are built by their own hands. Kere was very committed to his village and neighbors. This social responsibility was shown in his keenness on training people to ensure sustainability of the built projects. He encouraged the community to use their skills in earning money as through this way people would stay in the country and strengthen the community. His main motto was that when power of the community is used in architecture, it would help everyone making their own future. Despite the community’s illiteracy, he succeeded to engage locals through explaining his engineering theories through prototypes. Kere helped preserving the social sustainability, community identity and improving the national economy through using traditional and well tested techniques and local materials.
such as compressed clay blocks and raised the roof with cheap steel bars. He strived for creating thermal comfort in the school, especially because the high temperature, which reaches 45°C in Burkina Faso. The success of Kere projects and CSR approach did not stop at the school but continued to include a library for the community (Kere, 2013). Marketing strategies should be designed so as to reflect and fulfill customer needs; whether they are known needs or they are unspoken needs that require research and studies. When the Global CSR studies prove that the consumers’ awareness levels of social responsibility (CONE, 2015), then it goes without saying that CSR should be used in the marketing of ADFs. Some architects had used their skills differently; as much as they could have used their skills to promote a socially responsible concept, on the other side, they may use their skills to promote to consumerist concepts as well.

3. Research methodology
Due to nature of this study, the research methodology approach adopted was based on data collection, data analysis and action required, (Figure 1). Data collection are a principal activity in the research process. Data were collected from different sources, using different methods to achieve certain objectives. This was known as “triangulation,” which increased the reliability and validity by verifying findings of data from one source with other sources. This strategy reduces the risk and bias associated with using specific methods (Maxwell, 1996):

- Data collection was based on literature review and survey questionnaire. Firstly, the literature review resources depended on textbooks, academic and professional journals, conference and seminar proceedings, dissertations and theses, organizations and government publications and internet and related websites. Data collected from literature review focused on examining the concepts of marketing and CSR in construction. Secondary, results of a survey questionnaire conducted with a representative sample of ADFs in Egypt were presented and analyzed to investigate

![Figure 1.](image-url)  
The research methodology (developed by the authors)
the perception and application of CSR as a novel approach for marketing ADFs in developing countries. The survey consisted of open ended questions (e.g. thoughts and opinions) and close ended questions (e.g. Yes/No questions, rating questions based on one-five Likert scale). A pilot study of the survey was tested with colleagues to determine its effectiveness and problems. After going over the responses of the preliminary test and making changes, the questionnaire was ready for formal testing (Baker, 1994; Czaja and Blair, 1996).

- A two-stage approach was adopted for data analysis. The first stage was simply to measure the central tendency and dispersion of the questionnaire responses. The measure of central tendency was used to get an overview of the typical value for each variable by calculating the mean, median and mode. The measure of dispersion was used to assess the homogenous or heterogeneous nature of the collected data by calculating the variance and the standard deviation (Bernard, 2000). Secondly, as not all criteria for selecting ADFs have the same importance to clients the relative importance index (RII) was used to differentiate between these criteria (Olomolaiye et al., 1987; Shash, 1993). The data were analyzed with the aid of Microsoft Excel spreadsheet. Analysis of the collected data showed close values of means, medians and modes, indicated typical central values and showed also low values of variance and standard deviation. This confirmed the quality and the homogeneity of the collected data and a low degree of dispersion resulting in reliable findings.

- Based on the results of data collection and data analysis, a proposed framework based on CSR was developed for marketing ADFs in developing countries.

3.1 Questionnaire survey sample
The sampling plan using a random probability sampling method was applied to the population size, which was 44 ADFs registered in the Egyptian Engineers Syndicate (EES) (2018). This allowed every unit an equal chance of being included in the sample (Hannagan, 1986; de Vaus, 1990). This helped selecting a representative and non-biased sample. To calculate the sample size, the next two equations were used (FluidSurveys Team, 2014):

$$\text{Sample Size Calculation} = \left[ \frac{\text{Distribution of 50\%}}{\text{Margin of error\%} \times \text{Confidence Level Score}} \right]^2$$

$$\text{True Sample} = \frac{\text{Sample Size Level Score}}{\text{Sample Size} + \text{Population}}$$

In this research, the confidence level chosen is 95 per cent and the margin of error is 5 per cent. The confidence level score corresponding to the confidence level of 95 per cent is 1.96:

$$\text{Sample Size} = \frac{0.5 \times (1.51)}{[0.05 / 1.96]^2} = 384.16$$
True Sample = \frac{384.16 \text{ mpl}}{384.16 + 44 \text{ le}} = 39.57 \sim 40

However, as the true sample size is only different from the population size by 4; the population size would be considered entirely for the survey questionnaire.

4. Data analysis

This section presents the results of a survey questionnaire conducted with a representative sample of ADFs in Egypt to investigate their perception and application of CSR as a marketing tool in developing countries.

4.1 Response rate and respondents' profile

Out of 44 ADFs, only 32 firms responded to the survey questionnaire, which represents 72.7 per cent. The number of years of experience of these firms in the construction industry ranges from 10-60 years. They are involved in all types of projects including residential, commercial, medical, industrial, cultural, business, recreational and educational. The size of these firms ranges from 10-50 employees with architecture, engineering and constructions backgrounds. The survey questions were answered by the Head of the design team in ADFs. They have from 10 to 25 years of experience with age ranges from 35 to 50 years old. They have diverse area of knowledge, skills and participated in projects of different scales nationally or internationally.

4.2 Perception and application of corporate social responsibility as marketing tool in Egyptian architectural design firms

- A total of 66 per cent of the surveyed ADFs stated that they are not adhering to any national or international regulations about social responsibility. Architects in 47 per cent of the surveyed firms are unaware of their firms’ strategies and visions. None of the surveyed ADFs has any of the social responsibility aspects in their visions. A total of 66 per cent of the architects are unaware of the firm’s reputation and image and accordingly the significance of the firm’s image in the marketing process.

- A total of 31 per cent of the respondents are well acquainted with the concept of CSR and its aspects. However, the CSR is not included in their strategies or visions. On the other hand, 38 per cent of the respondents are moderately interested in participating in socially responsible activities and projects. This reflects the influence of the obstacles that hinders the actual application of socially responsible projects. These obstacles are ranked according to their importance as shown in Figure 2.

- Most of architects in the surveyed sample believe that clients choose ADFs based the following categories ranked according to their relative importance index (RII) (Figure 3).

- A total of 75 per cent of respondents are interested in engaging in socially responsible projects, with actual involvement in the practices not only as an image but also for publicity; while 66 per cent of the architects in the surveyed sample agree upon the success of involving CSR as a marketing strategy for ADFs.

- A total of 72 per cent of respondents stated that “the lack of the architects’ experience on how to integrate CSR concept” and 53 per cent considered “financial incapability” as the main obstacles to engage ADFs in socially responsible projects.
5. A proposed corporate social responsibility framework for marketing architectural design firms in developing countries

According to the results of the literature review and survey questionnaire, the research proposed the development of a framework based on CSR as an approach for marketing ADFs in developing countries.

5.1 Definition and background

Framework is defined as a set of notions, techniques and tools in a planned outline to complete a product, process and design (EDMS, 2010). The CSR framework for marketing architectural design firms (CSR4MADFs) in developing countries (hereinafter referred to as “the framework” or “CSR4MADFs”) is a proposed framework developed by this research to integrate CSR aspects in the marketing strategies of ADFs in developing countries.

![Obstacles of engaging in CSR activities in ADFs](image)

**Figure 2.** Obstacles of engaging in CSR activities in ADFs

![Client’s categories for choosing ADFs](image)

**Figure 3.** Client’s categories for choosing ADFs
5.2 The need for the framework
The CSR4MADFs is needed so as to provide a structured plan to overcome the current marketing strategies’ deficiencies in ADFs. The current marketing strategies are insufficient in terms of providing the required support to the community within which they operate. This framework is to be applied in developing countries, where the communities suffer from many problems such as poor health conditions, poor sanitation and poor educational systems and facilities. The integration of the CSR concept in the marketing strategies of ADFs would provide firms with the needed marketing goals; and enhancing the living conditions of the communities in developing countries.

5.3 Development of the framework
The development of the framework was based on the results of the literature review and data analysis gleaned from the survey questionnaire. Literature review showed that adopting CSR as a marketing tool received scant attention in construction literature, especially in ADFs in developing countries. However, there are emerging calls for integrating the marketing activities along with the socially responsible goals. These findings are in line with results of the survey questionnaire. Respondents confirmed that their firms are not adhering to any social responsibility regulations and they are unaware of their firms’ strategies and visions about CSR. Results showed that there are many barriers that hinder the adoption of CSR as a marketing tool. These included, for instance, lack of architect’s experience in CSR activities and financial incapability. In addition, the majority of surveyed ADFs were interested in integrating CSR in their marketing strategies.

5.4 Aim of the framework.
The CSR4MADFs is an innovative conceptual business improvement tool used to enhance the current marketing strategies in ADFs, through the integration of the CSR concept. This will help enhancing the marketing process of ADFs and improving the living conditions of developing countries.

5.4 The conceptual description of the framework
The framework consists of five functions, namely:

(1) identifying integration problem;
(2) establishing integration objectives;
(3) developing integration plans;
(4) executing integration plans; and
(5) monitoring the integration plans (Figure 4).

5.5.1 Identifying integration problem. The “identifying integration problem” function is an essential activity of this framework because it enables ADFs to identify the core causes that obstruct the integration of CSR into the marketing strategies in ADFs. It is of importance to build an effective team (including a competent team leader) to carry out the integration study. Achieving a balance between the need for participants who represent various areas of expertise and possess diverse background is fundamental for accomplishing the study objectives. The study team should contain between 6 and 12 full time participants to maintain optimum productivity (Norton and McElligott, 1995). Performing an early orientation meeting will help in establishing strategic issues such as study duration, resources required and assigning responsibilities to team members. Senior management support will facilitate the provision of needed resources and the adoption of study decisions and recommendations. Data collection methods (i.e. literature review, survey questionnaire, interviews and case studies) and data
analysis techniques (i.e. quantitative and qualitative) have to be defined and used. Brainstorming technique, team consensus and evaluation matrix have to be used for identifying the root causes and rank them according to their importance.

5.5.2 Establishing integration objectives. Toward improving the marketability of ADFs in developing countries, the objectives of integrating CSR into the marketing strategies of ADFs have to be adequately established and agreed by all participants. This could be achieved through using brainstorming technique and team consensus to generate and select objectives that address the identified problem. Establishing integration objectives gives team members ownership to these objectives and encourages the study team to accomplish them. Evaluation matrix will be used to rank these objectives according to their significance. In addition, this function will result also in defining the criteria to be used to measure the improvement of marketing of ADFs in developing countries.

5.5.3 Developing integration plans. The “developing integration plans” function aims to set the procedures and actions necessary to accomplish the integration objectives. It will include a work breakdown structure and a responsibility matrix, where the first downsizes the work into manageable work packages and the later links the activity to be done and the responsible person. In addition, the plans should include expected risks and corrective actions to be taken in case of the plan did not go as planned. Furthermore, the communication plan between the study team has to be developed to portray the reporting structure during the integration of CSR into marketing strategies of ADFs in developing countries.

5.5.4 Executing integration plans. Within this function, the plans developed in the previous function will be executed. The execution plans may require that employees involved in the integration process be trained and equipped with all tools and technologies required to guarantee the successful execution of plans. In addition, senior management support and offering the required facilities will help achieving the integration objectives. The execution function should use the work authorization system, which verifies the predecessor activities and permits the successor activities to proceed. This ensures the quality of work performed.
5.5.5 Monitoring and evaluating the integration plans. The aim of this function is to ensure that the integration of CSR into the marketing strategies of ADFs in developing countries goes according to plans. Comments and feedback from the execution team will enable taking corrective actions if plans were not implemented as planned. Furthermore, this will help improving the performance of ADFs in future improvement projects.

5.6 Benefits and limitations of the framework

The benefits of the framework will impact positively on ADFs and the community within which they operate in developing countries. The benefits lie in providing ADFs with an innovative tool for enhancing their marketing strategies through including the CSR aspect. The CSR4MADFs provides solutions to the deficiencies in the current marketing strategies, including neglecting the community needs and imposing alien cultures on them. Implementing the framework will enhance the living conditions of the communities in developing countries, through public participation and the involvement of the social obligation in the strategies of ADFs. However, the CSR4MADFs is hindered by the poor awareness of ADFs about the application of CSR aspects in real life projects. Moreover, the framework’s success depends on the encouragement of ADFs and the government to facilitate the integration process. The application of the framework is time consuming process, which requires full dedication from the participants. Due to the nature of the construction industry and time constraints of projects, this framework may not be welcomed and ADFs may be reluctant to conduct this integration.

6. Conclusion and recommendations

Developing countries, in which 85.4 per cent of the world population lives in, are lands of contrasts. In spite of the great mineral wealth, geographic locations, human resources, agricultural exports and reasonably sophisticated manufacturing and services sectors, the majority of the people are poor and large parts of the countries are underdeveloped and suffer from inadequate basic facilities and services such as clean water, health care, sanitation and electricity. Governments in developing countries are in charge of achieving sustainable development objectives through delivering projects and infrastructure facilities that fulfill community needs. Through their technical capabilities, ADFs play a pivotal role toward supporting governments attaining these objectives. The escalating number of ADFs in developing countries resulted in a fierce competition between these firms to win new projects. This offered clients the opportunity to select the most appropriate firm based on their resources, capabilities, problem-solving approaches and experiences. Accordingly, ADFs that fail to support their products and services face the risk of losing their customers, competitiveness and market share. The research discussed the inefficiency of current marketing strategies of ADFs in developing countries due to lack of considering community needs, using incomprehensible technical language in communication with clients and misrepresenting the calibers of ADFs. ADFs, which aim to remain in market and compete for the future have to adopt innovative marketing strategies. CSR is one of the promising tools for marketing ADFs as it focuses on enhancing the community and meeting its requirements, which is aligned with the architect’s role, especially in developing countries. Consequently, this paper investigated the perception and application of CSR as an approach for improving the marketability of ADFs in developing countries. This was achieved through a survey questionnaire conducted with a representative sample of ADFs in Egypt. Based on literature review and survey results, this paper proposed a framework based on CSR as a novel approach for marketing ADFs in developing countries. This ideology has received scant attention in construction literature. The developed framework represents a synthesis that is novel and creative in thought and adds value to the knowledge in a
manner that has not previously occurred. Accordingly, the research comes to the following recommendations to government, ADFs and future research:

- adopting CSR as a novel approach for marketing ADFs in developing countries through applying the developed framework in Egypt and testing its applicability and evaluating its results. Accordingly, the developed framework shall be updated to suit Africa and other developing countries;
- engaging employees in developing their firms’ visions, missions and strategies. In addition, raising the awareness of employees toward the importance of their social interaction with communities;
- providing senior management of ADFs with successful examples to facilitate the adoption of CSR as a marketing tool in developing countries and provide the needed resources and allow ample time for implementation to ensure successful results;
- providing governmental incentives for ADFs that successfully engage in CSR activities to enhance the living conditions of communities in developing countries; and
- conducting the same study in construction and allied industries in an effort to create increased awareness of CSR in the built environment and to guide implementation of CSR in other engineering disciplines.

References
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Analysis of the outcome features of effective monitoring and evaluation in construction project delivery

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Abstract

Purpose – This study aims to analyze the outcome features of effective monitoring and evaluation in construction projects delivery.

Design/methodology/approach – The study adopted a quantitative research approach. Questionnaire survey was administered to 230 participants who were drawn from metropolitan, municipal, district assemblies and regional coordinating councils in Ghana. Data collected were analyzed to determine the key and underlying monitoring and evaluation outcome features in project delivery. A Cronbach’s α value of 0.953 was achieved based on standardized items, while the Kaiser–Meyer–Olkin measure of sampling adequacy recorded was 0.876. The result of Bartlett’s test of sphericity also revealed a significance level of 0.000 (p < 0.05).

Findings – The study discovered that value for money, successful project closure, end-user satisfaction, timely completion of projects and fitness for purpose were the top five monitoring and evaluation outcome features. Similarly, three principal monitoring and evaluation outcome features were identified, namely, performance, satisfaction and value outcome.

Practical implications – The study, thus, seeks to guide project planning and implementation of effective construction project M&E.

Originality/value – The study contributes to the body of knowledge by establishing top and key success outcomes (KSO) in the implementation of monitoring and evaluation.

Keywords Evaluation, Construction, Monitoring, Factor analysis, Outcome features

Paper type Research paper

Introduction

Globally, the construction industry is the focal point around which development revolves with far-reaching implication of its activities on the economy (Odediran et al., 2012). It is, therefore, necessary to effectively plan, monitor and control the activities of the industry.
The nature and complexity of the construction industry require a methodological approach in the management of project activities. This will ensure that planned activities are well coordinated to result in the expected project outcomes. To ensure that deployed materials, plants, labor and managerial expertise yield the expected project outcomes, the management of project resources is critical (Ugochukwu and Onyekwena, 2014). Thus, in managing projects for successful outcomes, it is imperative to closely monitor and evaluate project activities. While effective monitoring and evaluation can lead to successful project outcomes, several factors, including the type of project stakeholders and their interest in projects and the nature and scope of projects, have resulted in divergent project outcomes. Tengan and Aigbavboa (2017) found that, while clients, contractors and professional service providers are integral in the monitoring and evaluation of projects, achieving the agreed project cost was of great concern to clients, whereas contractors and professional service providers focused on successful project closure and performance. The object of monitoring and evaluation is to ensure project performance and successful project outcomes (Kimweli, 2013). These outcomes include achieving project quality, cost and schedule. However, the success rate of projects initiated particularly in the construction industry globally, but particularly in Africa is a mirage. Several factors have accounted for the poor global outlook of the construction industry with the issue of poor monitoring and supervision of the construction process being topical (Williams, 2015). According to Ile et al. (2012), monitoring provides a continuous generation of information about the progress being made toward the achievement of project results. Likewise, Otieno (2000) describes evaluation as measuring the extent to which project objectives have been met, based on the data and information generated through monitoring. It is, therefore, becoming increasingly necessary to effectively plan and implement the monitoring and evaluation process if project success outcomes are to be achieved.

Outcome features of effective monitoring and evaluation
Several studies have explored the need for monitoring and evaluation as a project management tool in achieving project success. Otieno (2000), Tache (2011) and Kamau and Mohamed (2015) discussed a plethora of benefits that are achieved through the effective M&E of projects. The object of monitoring and evaluation implementation seeks to guarantee ultimate project success through the achievement of immediate project outcomes such as conformity to standards and the achievement of budget and schedule, as well as long-term objectives such as fit for purpose (impact). The collective achievement of all immediate outcomes indicates that M&E are effective and, therefore, the success of the project is achieved (Papke-Shields et al., 2010; Chin, 2012; Ika, Diallo and Thuillier, 2012). A study by Papke-Shields et al. (2010) revealed that conformity to project specification (quality) would be achieved when projects are effectively monitored and evaluated. The study further emphasizes the achievement of projects within the approved budget (cost) and project duration (time) when M&E are effectively undertaken (Papke-Shields et al., 2010). Further, human organizational capacity and that of stakeholders are developed through effective M&E along with effective communication (Papke-Shields et al., 2010).

Beyond achieving direct project objectives such as cost, time and quality, organizations are afforded with the opportunity to learn (organizational learning) from previous practices and activities to help improve current and future projects implementation and better decision-making (Chipato, 2016). Donor agencies and project financiers are satisfied with the accountability level of projects that benefit from effective M&E practice, and this can ensure that in future such donors may release funding for development projects. Contractors are guided through the project implementation process which guarantees the
utmost performance of contractors. An effective project M&E practice ensures a healthy project implementation environment where all stakeholders are well represented on the project and given the opportunity to contribute to the project. Also, scarce project resources are committed to judicious use. A greater benefit of effective M&E is the assurance that project activities are done right the first time to eliminate rework (which is a likely contributor to increased project budget and extended project duration) arising from design and construction errors.

M&E activities also improve communication between different stakeholders. Effective M&E afford stakeholders a better understanding of implementation issues regarding all aspects of the project. To make communication effective, a constructive environment for exchange and discussion is essential. Clear and transparent communication mechanisms such as regular meetings, workshops, reporting and information sharing via the internet or printed media should also be established. It can, therefore, be concluded that the indicators of a successful project such as achieved project time, conformity to standards, achieving project cost, stakeholder satisfaction, contractor performance, health and safety, value for money, environmental performance, end-user satisfaction, client satisfaction and fitness for purpose are achieved through the effective implementation of M&E of projects.

Research methodology
The study adopted a quantitative research approach. The research approach comprised the review of literature and the administration of a questionnaire survey. The extensive literature study was to establish the outcome features of an effective monitoring and evaluation; 12 factors were identified, while the questionnaire survey helped to determine the main factors that can represent the outcome features of effective M&E in construction project delivery. A survey design according to Alreck and Settle (2004, p. 447) and Girden and Kabacoff (2011, p. 67) allow for the generalization of the study’s findings to the broader construction industry. The data were gathered from metropolitan, municipal and district assembly staff involved in the planning, monitoring and evaluation of projects at the local government level in Ghana via the survey questionnaire. The category of respondents was drawn from both the planning and engineering departments to ensure a fair representation of staff who had substantial knowledge and understanding of monitoring and evaluation at the MMDAs. The methods used to analyze data for the study are the mean item score (MIS) rating and the factor analysis (FA). The MIS was used in rating the mean score for each outcome feature based on the Likert scale from 5 to 1. For the study, it was used in ranking the level of importance of identified outcome features in M&E. The FA was also used to establish the variability among observed M&E outcome features. It also established the correlated variables in terms of a potentially lower number of unobserved variables called factors or constructs.

Data analysis and discussions
Demographic profile of respondents
The representation of males who responded to the questionnaire stood at 169, representing 73.5 per cent, while females constituted only 61, representing 26.5 per cent. This result suggests a male dominance of staff involved in the M&E of projects at the local government level. The academic qualifications of the respondents also showed a fairly true reflection of the situation. A majority of respondents who possess bachelor’s degrees made up 78, representing an aggregate of 33.9 per cent. This was followed by the holders of a master’s degree who constituted 65, representing 28.3 per cent. A total of 45 of the respondents (19.6
per cent) held HND/national diploma, whereas 42 respondents representing 18.3 per cent possessed postgraduate certificates.

The role and status of the respondents at the local government were also of interest to the current study. This was to ascertain whether there is a true representation of relevant departments at metropolitan, municipal and district assemblies (MMDAs) and whether the regional coordinating council (RCC) charged with the M&E of projects is well represented in the study. Two broad department/units constituted the target population. In that respect, 132 respondents representing 57 per cent were from the planning departments of the MMDAs/RCCs. This representation from the planning departments can further be broken down as 74 respondents representing 32.2 per cent; \( n = 74 \) as planners, 29 coordinating directors (12.6 per cent; \( n = 29 \)) and chief executive officers and budget officers constituted 4.8 per cent; \( n = 11 \) and 7.8 per cent; \( n = 18 \). Likewise, 98 or 43 per cent worked in the engineering department and comprised engineers who constitute 49 representing 21.3 per cent; \( n = 49 \). Also, 39 quantity surveyors represented 15.2 per cent; \( n = 39 \), while architects constituted 6.1 per cent; \( n = 14 \).

The representation of MMDAs in the study stood at 4.8 per cent; \( n = 11 \) of metropolitan assemblies, 5.2 per cent; \( n = 12 \) of RCCs, 34.8 per cent; \( n = 80 \) representing municipal assemblies and 55.2 per cent; \( n = 127 \) representing the district assemblies in Ghana. Finally, the experience of the respondents at the MMDA was established to ascertain their level of experience regarding the years they have been working at the local government level. It was evident from the surveyed response that 98 of the respondents representing 42.5 per cent; \( n = 98 \) had been working between one and five years Also, 33.9 per cent; \( n = 78 \) of the respondents had between five and ten years of working experience with the MMDA. This is followed by respondents who had been working for less than a year (11.3 per cent; \( n = 26 \)), between 10 and 15 years (8.7 per cent; \( n = 20 \)) and above 15 years (3.5 per cent; \( n = 8 \)).

Descriptive analysis of monitoring and evaluation outcome features
The study sought to establish major outcome features when undertaking monitoring and evaluation of construction projects. The respondents who were planners, coordinating directors, budget officers, engineers, quantity surveyors and architects were asked to indicate the extent to which effective monitoring and evaluation will result in the outcome features presented based on their experience on projects they had been involved. The respondents were then requested to rate the 12 identified determining factors on a five-point Likert scale, where 5 represents extremely likely, 4 very likely, 3 somewhat likely, 2 slightly likely and 1 not at all likely. Outcome features with a mean score greater than 3.5 (population mean), (MS ≥ 3.5) was regarded as a likely outcome feature during the effective implementation of M&E (Ling, 2002 and Ahadzie, 2007). Table I presents the mean rankings of M&E outcome features.

From Table 1, all the 12 outcome features presented recorded mean score greater than 3.5. It is, therefore, suggestive that successful outcomes of project delivery significantly depend on the effective implementation of M&E. Similarly, it is observed that all outcome features recorded standard deviation scores less than one (SD < 1), providing grounds to suggest the extent of consistency in agreement among respondents (Ahadzie, 2007; Stevens, 1996). The outcome feature, value for money was rated highest with a mean score (MS) of 4.57 and standard deviation score (SD) of 0.675. Successful project closure (MS 4.53; SD 0.624), end-user satisfaction (MS 4.49; SD 0.652), timely completion of projects (MS 4.47; SD 0.610) and fit for purpose (MS 4.43; SD 0.607) were accordingly rated second, third, fourth and fifth, respectively. Achieving project cost (budget) was, however, rated eleventh with MS 4.28 and SD 0.724, while environmental performance was rated last (MS 4.21; SD 0.841)
Factor analysis of monitoring and evaluation outcome features

Tables 2, 3, 4 and 5 describe the Kaiser–Meyer–Olkin measure of sampling adequacy and Bartlett’s test, communalities extracted, total variance explained and rotated component matrix of the exploratory factor analysis conducted on the M&E outcome features respectively. The 12 items measuring the outcome of effective M&E in construction project delivery were subjected to exploratory factor analysis. The technique adopted for extraction and rotation were the principal component (PC) and varimax with Kaiser normalization, respectively.

Factorability of the correlation matrix was ensured before undertaking the analysis. The KMO measure of sampling adequacy and Bartlett’s test of sphericity were conducted. From Table II, the KMO recorded was 0.876 which is seen greater than the minimum cutoff of 0.7 to establish sampling adequacy (Hair et al., 2010). The result of Bartlett’s test of sphericity also revealed a significance level of 0.000 ($p < 0.05$). This result implies that a possible correlation exists among the variables, thus suggesting a realistic group forming factors from the variables and a justification to proceed with factor analysis (Field, 2009).

Further, the Cronbach’s $\alpha$ was computed, and a value of 0.904 was recorded, suggesting adequacy of internal consistency and reliability in the measures and the scale (Hair et al., 2013; Field, 2009). According to Field (2009), Cronbach’s $\alpha$ above 0.70 is acceptable for scale reliability and internal consistency of the instrument. Communalities extracted on each variable were assessed to help in deciding the variables that have to be finally extracted (see Table III). This criterion helped to determine which variables will be deleted or retained for further detailed analysis (Field, 2009).

The average communality of the variables after extraction computed and presented in Table III stood at 0.678, indicating that the extracted communalities support the use of factor analysis on the variables. According to Field (2009) and Motulsky (2005), the reliability of the results and interpretations in factor analysis is achieved with an average communality of 0.60 after extraction. Likewise, communality values of a potentially significant variable must yield an extraction value (eigenvalues) greater than 0.50 at the initial iteration (Field, 2009; Hair et al., 2013). This criterion determines the removal or inclusion of the variable for further detailed analysis to be undertaken. From the results presented in Table III, all 12 variables had an extracted eigenvalue among the likely outcome features of effective project M&E at the local government even though they recorded MS rating greater than 3.5.

<table>
<thead>
<tr>
<th>M&amp;E outcome features</th>
<th>N</th>
<th>MS</th>
<th>SD</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value for money</td>
<td>230</td>
<td>4.57</td>
<td>0.675</td>
<td>1st</td>
</tr>
<tr>
<td>Successful project closure</td>
<td>230</td>
<td>4.53</td>
<td>0.624</td>
<td>2nd</td>
</tr>
<tr>
<td>End-user satisfaction</td>
<td>230</td>
<td>4.49</td>
<td>0.652</td>
<td>3rd</td>
</tr>
<tr>
<td>Completion of project on time</td>
<td>230</td>
<td>4.47</td>
<td>0.610</td>
<td>4th</td>
</tr>
<tr>
<td>Fit for purpose</td>
<td>230</td>
<td>4.43</td>
<td>0.607</td>
<td>5th</td>
</tr>
<tr>
<td>Contractor performance</td>
<td>230</td>
<td>4.43</td>
<td>0.656</td>
<td>6th</td>
</tr>
<tr>
<td>Client satisfaction</td>
<td>230</td>
<td>4.41</td>
<td>0.666</td>
<td>7th</td>
</tr>
<tr>
<td>Achieving project conformity</td>
<td>230</td>
<td>4.34</td>
<td>0.598</td>
<td>8th</td>
</tr>
<tr>
<td>Achieving project sustainability</td>
<td>230</td>
<td>4.31</td>
<td>0.840</td>
<td>9th</td>
</tr>
<tr>
<td>Health and safety performance</td>
<td>230</td>
<td>4.30</td>
<td>0.783</td>
<td>10th</td>
</tr>
<tr>
<td>Achieving project cost (stay within budget)</td>
<td>230</td>
<td>4.28</td>
<td>0.724</td>
<td>11th</td>
</tr>
<tr>
<td>Environmental performance</td>
<td>230</td>
<td>4.21</td>
<td>0.841</td>
<td>12th</td>
</tr>
</tbody>
</table>
greater than the 0.50. Hence, all 12 variables were included for further analysis (Field, 2009; Hair et al., 2013).

When all necessary and required pre-checks and initial tests were concluded, exploratory factor analysis was then conducted using all 12 extracted variables. The eigenvalue and factor loadings were set at conventional high values of 1.0 and 0.5, respectively, as indicated in literature (Field, 2009; Liu, 2009; Hair et al., 2013). From Table IV, the total variance explained by the variables indicates that three components should be extracted from the data as their respective eigenvalues were greater than 1.00. Similarly, the rotated component matrix in Table V confirms the three unique component factors as each variable dominantly belonged to a single factor (component). It could be suggested, therefore, that the components that emerged are the perceived leading M&E outcomes of effective project M&E in the Ghanaian construction industry.

### Table II.

<table>
<thead>
<tr>
<th>Code</th>
<th>M&amp;E outcome variables</th>
<th>Initial</th>
<th>Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>C13M&amp;EOF1</td>
<td>Health and safety performance</td>
<td>1.000</td>
<td>0.545</td>
</tr>
<tr>
<td>C13M&amp;EOF2</td>
<td>Environmental performance</td>
<td>1.000</td>
<td>0.679</td>
</tr>
<tr>
<td>C13M&amp;EOF3</td>
<td>Successful project closure</td>
<td>1.000</td>
<td>0.698</td>
</tr>
<tr>
<td>C13M&amp;EOF4</td>
<td>Completion of the project on time</td>
<td>1.000</td>
<td>0.675</td>
</tr>
<tr>
<td>C13M&amp;EOF5</td>
<td>Client satisfaction</td>
<td>1.000</td>
<td>0.577</td>
</tr>
<tr>
<td>C13M&amp;EOF6</td>
<td>End-user satisfaction</td>
<td>1.000</td>
<td>0.664</td>
</tr>
<tr>
<td>C13M&amp;EOF7</td>
<td>Contractor performance</td>
<td>1.000</td>
<td>0.545</td>
</tr>
<tr>
<td>C13M&amp;EOF8</td>
<td>Achieving project cost (stay within budget)</td>
<td>1.000</td>
<td>0.764</td>
</tr>
<tr>
<td>C13M&amp;EOF9</td>
<td>Achieving project conformity</td>
<td>1.000</td>
<td>0.780</td>
</tr>
<tr>
<td>C13M&amp;EOF10</td>
<td>Achieving project sustainability</td>
<td>1.000</td>
<td>0.663</td>
</tr>
<tr>
<td>C13M&amp;EOF11</td>
<td>Value for money</td>
<td>1.000</td>
<td>0.748</td>
</tr>
<tr>
<td>C13M&amp;EOF12</td>
<td>Fit for purpose</td>
<td>1.000</td>
<td>0.799</td>
</tr>
</tbody>
</table>

**Note:** Extraction method: principal component analysis

### Table IV.

<table>
<thead>
<tr>
<th>Component</th>
<th>Total variance</th>
<th>Cumulative %</th>
<th>Total variance</th>
<th>Cumulative %</th>
<th>Total variance</th>
<th>Cumulative %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>5.863</td>
<td>48.859</td>
<td>48.859</td>
<td>5.863</td>
<td>48.859</td>
<td>48.859</td>
</tr>
<tr>
<td>Rotation</td>
<td>2.108</td>
<td>17.567</td>
<td>67.817</td>
<td>2.108</td>
<td>17.567</td>
<td>67.817</td>
</tr>
</tbody>
</table>

**Note:** Extraction method: principal component analysis
The results from Table IV present the total variance explained by each of the three extracted components. The principal component one accounted for 48.859 per cent of the total variance, whereas the second principal component accounted for 10.095 per cent of the total variance. The third and final principal component extracted also accounted for 8.864 per cent of the total variance in the M&E outcome effective construction project M&E. From this, it could be seen that the three components extracted cumulatively accounted for 67.817 per cent of the total variance which is above the recommended minimum of 50 per cent (Field, 2009; Motulsky, 2005).

The rotated component matrix was used over the ordinary unrotated matrix because of the ability of the rotated component matrix to yield and achieve a simple robust structure which presents an easy identification and interpretation of results (Field, 2009). Likewise, all the components extracted had more than one variable on them, informing that the results obtained are reasonable and free of complex structures (Field, 2009). Considering the possible interrelations among the variables contained in each component and the factor loadings, a more suitable name that summarizes the M&E outcomes explained by the components was derived. Thus, Component factor 1 was labeled as “performance outcome features”, while Component factor 2, on the other hand, was labeled as “satisfaction outcome features” and Component factor 3 as “value outcome features”.

The first component factor identified from the analysis was performance outcome features. The component is made up of six items, namely, successful project closure (80 per cent), environmental performance (79.4 per cent), client satisfaction (71.4 per cent), end-user satisfaction (66.2 per cent), health and safety performance (64.2 per cent) and contractor performance (63.2 per cent). The second component factor was established as satisfaction outcome features and comprised of three items which are achieving project conformity (quality) (83.5 per cent), achieving project cost (stay within budget) (79.0 per cent) and completion of the project on time (69.6 per cent). Finally, the third component factor was value outcome features with two items represented as fitness for purpose and value for money, with factor loadings 85.9 and 78.3 per cent, respectively. The numbers in parenthesis indicate the respective factor loadings on each item as presented in Table V. Similarly, this cluster of items making up the performance outcome features accounted for about 48.859 per cent of the total variance explained, whiles satisfaction and value outcome features accounted for about 10.095 and 8.864 per cent of the total variance explained, respectively.
**Discussion of findings**

From the findings, there is evidence of effective monitoring and evaluation leading to project success, thus achieving value for money, successful project closure, end-user satisfaction, completion of project on time, fit for purpose, contractor performance, client satisfaction, project conformity, project sustainability, health and safety performance, project cost (stay within budget) and environmental performance. These findings are consistent with the existing body of knowledge. For example, Papke–Shields *et al.* (2010) revealed that the quality of a project is achieved when effectively monitored and evaluated. Ikuabe and Oke (2018) also suggest that value for money is a highly anticipated project outcome because of the huge capital committed on projects. Similarly, the findings corroborate the plethora of studies that inform that the construction environment is given little attention, leading to the adverse impact of construction activities (Ametepey and Ansah, 2015; Ayarkwa *et al.*, 2014). The need, therefore, for environmental consideration and planning is critical in the M&E process. Also, while achieving project cost and ensuring that environmental performance of project sites was significant outcome features to be achieved via effective M&E, the low rating by monitoring and evaluation professionals is a course for concern. This finding reinforces the reason why cost overrun on project has become topical in project management research (Kissi *et al.*, 2018) and supported by the study of Williams (2015) informing that nearly one-third of projects implemented at the local government fails to meet the cost target of the project (Williams, 2015).

**Conclusion and recommendation**

As informed by the study, several project outcomes are achieved with effective monitoring and evaluation practice. These outcome features are influenced by the varied interest of stakeholders involved in project delivery and so, makes it difficult to plan to achieve project success. Hence, the study aimed at analyzing the outcome features of effective monitoring and evaluation in construction project delivery through a MS rating and factor reduction technique. The study identified the key outcome features in the implementation of monitoring and evaluation. The study revealed that value for money, successful project closure, end-user satisfaction, timely completion of projects and fitness for purpose are the top M&E outcome features to be achieved when undertaking effective construction project monitoring and evaluation. Staying within the project budget and ensuring project environmental performance appeared not to be a major concern for M&E implementors. The principal component analysis further established three major component features to be achieved during construction project M&E. These are performance, satisfaction and value. The findings of the current study provide far-reaching implications for both monitoring and evaluation research, practice and policy. The study contributes to the body of knowledge by establishing the top and principal components features of M&E outcomes in construction project delivery. For M&E practitioners, the finding presents the key success outcomes (KSO) in the implementation of monitoring and evaluation. Project resources will, therefore, be channeled toward critical activities to achieve these outcomes. With the limited outcome features, as presented in the study, coordination and collaboration among stakeholders is strengthened toward achieving the immediate and long-term impact of projects implemented. Policy-wise, the study’s findings will guide project planning and implementation of effective construction project M&E.
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**Further reading**


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Short run causal relationship between foreign direct investment (FDI) and infrastructure development

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Abstract

Purpose – Foreign direct investment (FDI) flows for infrastructure development have grown in volume to become more widely dispersed among home (outward investor) and host (recipient) countries. This paper aims to explore the short-run causal relationship between FDI and infrastructure development in the developing country of Ghana.

Design/methodology/approach – A two-stage least squares estimation method was adopted where FDI was endogenized, and all variables were in constant prices. Stationarity tests were performed on the annualized log difference of variables using augmented Dickey–Fuller test (ADF).

Findings – Results reveal a positive and significant relationship between FDI and infrastructure but a negative and significant relationship between FDI and GDP and FDI and openness. GDP growth also has a long-run negative relationship with FDI inflows.

Originality/value – The paper’s contribution to knowledge is two-fold. First, it examines the short run effect of FDI upon the Ghanaian economy and how market shocks to FDI and infrastructure development can be ameliorated. Second, it illustrates that government policymakers should prioritize development that requires FDI and ensure that the local market is not excessively open to foreign exploitation. Future work is required to further investigate international capital flow and its impact upon other developing nations.

Keywords Ghana, Infrastructure, Foreign direct investment (FDI), Sub-Sahara Africa, Gross domestic product

Paper type Research paper
Introduction
Since the early 1980s, global foreign direct investment (FDI) flow (estimated to involve over 54,000 transnational corporations) has grown faster than world trade and world output (Amiti and Wei, 2006). Agiomirgianakis et al. (2003) state that FDI can be defined as capital flows resulting from the behavior of multinational companies (MNCs) – thus, the factors to affect the behavior of MNCs may also affect the magnitude and the direction of FDI. FDI provides an important source of private external finance for developing countries and is primarily motivated by investors’ long-term desire to make profits in production activities that they directly control (Choe, 2003). While FDI represents investment in production facilities, its significance for developing countries is much greater (De Mello, 1999). FDI contributes to investible resources and capital formation but also facilitates transference of production technology, skills, innovative capacity, organizational and managerial practices and access to international marketing networks. Beneficiaries include enterprises operating within transnational systems but these opportunities can also transfer to domestic firms within a host country provided the economic environment is conducive (Blonigen et al., 2005). The greater the supply and distribution links between foreign affiliates and domestic firms, the stronger the domestic firms’ capabilities to enhance competitiveness (Sethi et al., 2003). Balasubramanyam et al. (1996) analyzed how FDI affects economic growth in developing economies. Using cross-section data and OLS regressions they (ibid) found that FDI has a positive effect upon economic growth in host countries using an export promoting strategy but not in countries using an import substitution strategy. Olofsdotter (1998) conducted similar analysis using cross sectional data and found that an increase in FDI stock is positively related to economic growth. The research (ibid) found that the effect is stronger for host countries with a higher level of institutional capability – as measured by the degree of property rights protection and bureaucratic efficiency in the host country. A more contemporary study by Olatunji and Shahid (2015), found a short-run dynamic relationship between FDI and economic growth, and suggested that the long-run relationship can be achieved through infrastructure development and political stability. However, extant literature also reveals that the main deterrents to attracting FDI in developing countries include: governance failure, problems of policy credibility, macroeconomic policy failures and poor liberalization policies (Anyanwu, 2011; Alfaro et al., 2004; Asiedu, 2003).

Given the aforementioned context, this paper seeks to explore the short run causal relationship between FDI and infrastructure development in the developing country of Ghana. Unlike previous studies on FDI that used cross-sectional data to examine the relationship between FDI, infrastructure and growth, this paper uses country specific data and further explores the effect of market shocks to FDI and infrastructure development. A greater understanding in this area of infrastructure development could help policymakers design effective policies to attract FDI inflow into sectors where investment is most needed.

Foreign direct investment
Growth in FDI accelerated in the 1990s, rising to $331bn in 1995 and $1.3tn in 2000 (UNCTAD, 2002). Consequently, developing countries experienced a sharp increase in the average ratio of FDI to total investment during the 1990s. A principal feature of FDI growth has been its meteoric rise in the services sector, which is now the dominant sector in global FDI. For developing countries, FDI in the services sector increased at an annual rate of 28 per cent over the period 1988 to 1999 but by 1999 it accounted for 37 per cent of total foreign investment inflows. A significant part of this increase has been the growth in private capital flows for infrastructure in response to the general trend towards privatization of

FDI inflows have been inconsistent and in 2012 they decreased in all three major economic groups – developed, developing and transition economies albeit at different rates (Asiedu, 2002; Seabra and Flach, 2005). In developed countries, FDI flows fell by 32 per cent to $561bn while many European Union (EU) countries and the USA experienced significant drops in their FDI inflows (WIR, 2012). Interestingly, FDI flows to developing economies remained relatively resilient, declining by only 4 per cent (World Bank, 2012). FDI inflows to small economies rose further in 2012 from $56bn in 2011 to $60bn, owing to the strong growth of FDI to least developed countries (LDCs) and small island developing States (SIDS). Outward FDI from developed economies declined by $274bn in 2012, accounting for almost all of the fall in global outward FDI. In contrast, FDI flows from developing economies rose by 1 per cent in 2012, amounting to $426bn. FDI outflows from Africa nearly tripled while flows from Asia, Latin America and the Caribbean remained constant at the 2011 level (World Bank, 2012).

Africa is one of the few regions to enjoy year-on-year growth in FDI inflows since 2010. Investment in exploration and exploitation of natural resources, and high investment from China both contributed to the current level of inward flows (WIR, 2012). More generally, the continent’s good economic performance (i.e. GDP grew by 5 per cent in 2012) underpinned the rise in investment. In Mauritania, FDI inflows doubled to $1.2bn, partly attributable to an expansion in mining operations (copper and gold) by Canada-based First Quantum Minerals and Kinross. Central Africa attracted $10bn of FDI in 2012, a surge of 23 per cent on the previous year. Recent natural resource discoveries also contributed to the increase in FDI inflows to East Africa, from $4.6bn in 2011 to $6.3bn in 2012 following the discovery of gas reserves in the United Republic of Tanzania and oil fields in Uganda (WIR, 2012). Outward FDI flows from Africa nearly tripled in 2012, from $5bn in the previous year to an estimated $14bn. In contrast, FDI flows to West Africa declined by 5 per cent, to $16.8bn, mainly because of decreasing flows to Nigeria caused by a toxic combination of political insecurity and the weak global economy (World Bank, 2012). Slowing FDI inflows to the Congo were offset by an increase to the Democratic Republic of the Congo, where inward FDI flows jumped from $1.7bn to $3.3bn. Some of the flows went towards the expansion of the copper-cobalt Tenke Fungurume mine.

**Foreign direct investment in Ghana**

Foreign capital (both direct and indirect investment) is constantly in demand (Agionirgianakis et al., 2003). Loans from international commercial banks were initially favored but during the 1980s, commercial bank lending dried up because of debt crises and forced many countries to reform their investment policies to attract more stable forms of foreign capital – including FDI (WIR, 2012). Developing world governments proactively seek economic policies reform (such as domestic labor market conditions, corporate taxes, tariff barriers, subsidies and privatization) to improve FDI activity in their countries (ibid). However, only a few sub-Saharan African countries have been successful in attracting significant FDI inflows. The historical trend of FDI inflows into Ghana can be aggregated
into three main phases (Tsikata et al., 2000). During 1983-1988, sluggish inflows were recorded, averaging about $4m per annum with the highest and lowest inflows being $6m in 1985 and $2m in 1984. During 1989-1992, moderate inflows were recorded, averaging about $18m per annum with the highest and lowest being $22m in 1992 and $14.8m in 1990 respectively. During 1993-1996 oscillatory inflows occurred which peaked in 1994 at $233m but fell by > 50 per cent the following year to $107m. The latest value of FDI in Ghana during 2013 was ($3,226,300,000.00 (US$). Tsikata et al. (ibid) suggest that a three-way nexus of economic growth, investment and political stability is an important feature of FDI inflows- particularly since Ghana’s coup d’état of 1972. During this period, a growth rate of 2.3 per cent was recorded, accompanied by > 60 per cent drop in FDI (from $30.6m in 1971 to $11.5m in 1972). Similar trends were experienced after the 1979 and 1981 coup d’état when growth fell to as low as 3.2 per cent. The state of the economy worsened further with a negative growth rates of -3.5 per cent in 1981 to -6.9 per cent in 1982; however inflow of FDI remained constant at $16.3m (ibid).

**Antecedents of foreign direct investment**

Various theories developed to explain the determinants of FDI are incapable of providing a generic theory that explains all variants (i.e., outward and inward FDI at the firm, industry and country level) (Itaki, 1991). However, Dunning (1993) describes three main types of motive-based FDI from the investment firms’ perspective, namely: i) *market-seeking* (or horizontal) FDI aims to serve local and regional markets replication of production facilities in the host country. Tariff-jumping or export-substituting FDI is a variant of this type of FDI; ii) *resource-seeking* (or vertical) which involves firms investing abroad to obtain scarce resources such as natural resources, raw materials or low-cost labor (World Bank, 2012). In contrast to market-seeking FDI, resource-seeking FDI involves relocating parts of the production chain to the host country; iii) *efficiency-seeking* occurs when a firm can gain from the common governance of geographically dispersed activities in the presence of economies of scale and scope (WIR, 2012). In 1998, the World Investment Report, UNCTAD (1998) analyzed the determinants of FDI and classified these into three thematic groups, namely:

1. political factors;
2. business facilitation; and
3. economic factors.

However, the absence of a generally accepted theoretical framework has led researchers to rely on empirical evidence (such as market size and openness) for explaining the emergence of FDI.

**Market size**

Artige and Nicolini (2005) and Pärletun (2008) state that market size as measured by GDP (or GDP per capita) is the most robust market-seeking FDI determinant in econometric studies yet, GDP is irrelevant for resource-seeking FDI (Artige and Nicolini, 2005). Jordaan (2004) proffers that FDI flows to countries with larger/expanding markets and greater purchasing power because firms can receive a higher return on investment. A larger market enables the efficient utilization of resources and exploitation of economies of scale; hence, a positive correlation exists between market growth and FDI (Charkrabarti, 2001). The Overseas Development Institute (ODI), 1997, state that this correlation serves as a proxy for the size of GDP and some of its characteristics (such as average income levels). Jaspersen et al. (2000) use the inverse of income per capita as a proxy for the return on capital and
conclude that real GDP per capita is inversely related to FDI/GDP. Schneider and Frey (1985), Tsai (1994) and Asiedu (2002) suggest that a higher GDP per capita implies better prospects for FDI in the host country.

**Openness**

Openness is a ratio that measures the relationship between exports/importsi to GDP (Charkrabarti, 2001). A country’s degree of openness to international trade will impact on FDI dependent upon the type of investment (Jordaan, 2004). When investments are market-seeking, trade restrictions (and therefore reduced openness) can have a positive impact on FDI as a result of ‘tariff jumping’. Traffic jumping occurs when foreign firms seek to serve local markets by establishing subsidiaries in the host country (ibid). In contrast, MNCs engaged in export-oriented investments may prefer to invest in a more open economy since increased imperfections that accompany trade protection generally imply higher transaction costs associated with exporting (Kravis and Lipsey, 1982; Wheeler and Mody, 1992).

**Labor costs and productivity**

Charkrabarti (2001) claims that labor costs (or wages) are the most contentious of all the potential determinants of FDI. Affordable labor is essential to attracting multinationals however, how wage levels affect FDI remains largely debatable. Goldsbrugh (1979), Saunders (1982) and Schneider and Frey (1985) demonstrate that higher wages discourage FDI. Conversely, Tsai (1994) suggests that high wages are not always a barrier to FDI. For example, the ODI (1997) suggest that when wage rates vary little from country to country, the skills of the labor force exert an impact upon decisions about FDI location.

**Political risk**

According to ODI (1997), politically instable host countries laden with rich natural resources are attractive to FDI because high returns compensate for risks posed. For example, large mining companies have overcome political risks by investing in their own infrastructure maintenance and security forces (Jaspersen et al., 2000). These companies are limited neither by small local markets nor by exchange-rate risks because they sell almost exclusively on the international market at hard currency prices. Specific proxy variables (e.g. number of strikes and riots and work days lost) have proved significant in some studies but these quantitative estimates can only capture some aspects of the qualitative nature of political risk. Indeed, the empirical relationship between political instability and FDI flows remains unclear within extant literature. While Jaspersen (ibid) and Hausmann and Fernandez-Arias (2000) find no relationship between FDI flows and political risk, Schneider and Frey (1985) find an inverse relationship between the two variables.

**Infrastructure**

Poor infrastructure presents both an obstacle and opportunity for FDI (ODI, 1997). For many low-income countries, inadequate infrastructure represents a major constraint but foreign investment can be attracted when host governments permit substantial foreign participation in national infrastructure development (ibid). Jordaan (2004) claims that good quality and well-developed infrastructure increases the productivity potential of investments and therefore stimulates FDI flows into the country.
Growth
The relationship between growth and FDI remains largely inconclusive. Lunn (1980) states that a rapidly growing economy provides relatively better opportunities for making profits than the ones growing slowly or not growing at all. Later research published by Lin (1983), Schneider and Frey (1985) and Ganstanag et al. (1998) confirm the presence of a significantly positive effect of growth upon FDI. However, time series analysis conducted by Tsai (1994) produced conflicting evidence of a positive correlation over the survey period 1983 to 1986 but a weak correlation between 1975 to 1978. This weak correlation between this growth and FDI was supported by Nigh (1985) and Ancharaz (2003).

Tax
Tax is also a contentious issue. Hartman (1994), Grubert and Mutti (1991), Hines and Rice (1994), Loree and Guisinger (1995) and Kemsley (1998) suggest that host country corporate income taxes have a significant negative effect on attracting FDI flows. However, Wheeler and Mody (1992), Jackson and Markowski (1995) and Porcano and Price (1996) conclude that taxes do not have a significant effect on FDI.

The direction of the effects of above mentioned determinants may positively or negatively affect FDI. Moosa (2005) states that due to the absence of a consensus on a theoretical framework to guide empirical work on FDI, there is no widely accepted set of explanatory variables that can be regarded as the “true” determinants of FDI.

Theories on foreign direct investment
Early works of FDI theory can be attributed to MacDougall (1958) who established his model based on the assumptions of a perfectly competitive market. This theory (ibid) was further elaborated upon by Kemp (1964). Assuming a two-country model and prices of capital being equal to its marginal productivity, MacDougall (1958) and Kemp (1964) both stated that when there was free movement of capital from an investing country to a host country, the marginal productivity of capital tended to be equalized between the two countries. They found that after investment, the output of the investing country fell without any decrease in the national income of the country. This is because in the long term, the investing country receives higher income from its investment abroad. Since this early work a number of alternative and/or supplementary theories have been developed.

Industrial organization approach
Hymer (1976) established the systematic industrial organization approach towards the study of FDI. This theory sought to explain international production in an imperfect market framework and was supported by Lemafalussy (1961), Kindleberger (1969), Knickerbocker (1973) and Dunning (1974). The industrial organization theory asserts that firms operating abroad have to compete with domestic firms that are in an advantageous position in terms of culture, language, legal system and consumers’ preference. Furthermore, foreign firms are also exposed to foreign exchange risk. These disadvantages must be offset by some form of market power in order to make international investment profitable.

Foreign direct investment based on monopolistic power
Kindleberger (1969) extended Hymer’s work (1976) and argued that advantages enjoyed by MNCs could be useful only in the case of market imperfection such as superior technology, managerial expertise and patents. These advantages encourage firms to invest in a foreign market in order to fully exploit them vis-a-vis share them with potential competitors.
Greater opportunities to earn monopoly profits encourage more firms to invest directly. Although, Kindleberger (1969) described various forms of advantages enjoyed by a foreign firm (over the host country firm), the specific advantage upon which a firm should focus was not elucidated upon. Further, a firm can only exploit its monopolistic advantages abroad if the host country’s policies allow it to do so – often and in the name of national interest, a host Government would be unwilling to permit free entry of foreign firms into the country.

**Internalization theory of foreign direct investment**

Buckley and Casson (1976) conceptualized FDI by emphasizing intermediate inputs and technology and shifting the focus of international investment theory away from country-specific towards industry-level and firm-level determinants of FDI (Henisz, 2003). Buckley and Casson (ibid) analyzed MNCs within a broad-based framework developed by Coase (1937). Buckley and Casson (1976) articulated their theory based upon three postulates that:

1. firms maximize profits in a market that is imperfect;
2. when markets for intermediate products are imperfect, there is an incentive to bypass them by creating internal markets; and
3. internalization of markets across the world leads to MNCs.

**Oligopolistic theory explaining foreign direct investment**

Knickerbocker’s (1973) theory was also formulated based on market imperfections. The three important motives for choosing a particular country as a new business location are:

1. firms seek increased access to the host country’s market;
2. firms want to take advantage of the relatively abundant natural resources available in that country; and
3. firms might invest in a country to match a rival’s move and avoid the risk of being underpriced (Head et al., 2002; Altomonte and Pennings, 2003).

**Eclectic paradigm to foreign direct investment**

Dunning (1977 and 1979) amalgamated the major imperfect market (i.e. oligopolistic and internalization theories) and added a third ‘location theory’ dimension explain why a firm opens a foreign subsidiary. Location theory seeks to determine who produces what goods or services in which locations and why? Enumerated factors considered include host country policies, economic fundamentals, firm strategy and agglomeration economies.

**Endogenous growth theory**

suggests that economic growth is generated by factors such as economies of scale, increasing returns on investment or induced technological changes which are within the production process (Romer, 1990). Grossman and Helpman (1991) developed growth models within the endogenous growth theory to explain the relationship between FDI and growth. These models assume that technological progress (including knowledge transfer and innovation) is the principal driving force of economic growth. Therefore, these models place emphasis on human capital accumulation and externalities on growth. Developing countries are generally unable to innovate and generate new technologies, therefore they adopt technology(ies) produced from advanced countries through FDI. New growth theories
indicate bidirectional causality between FDI and growth (Borensztein et al., 1998). This is because FDI is expected to improve economic growth by encouraging the incorporation of new foreign technologies in the production function of the beneficiary country. FDI also enhances growth by adding to the host country’s existing knowledge base through human resource training and development and increases competition in the host country by overcoming entry barriers and reducing the market power of existing firms (Dunning, 1993; Borensztein et al., 1998 and De Mello, 1999).

**Infrastructure and foreign direct investment**

FDI inflow is a key factor of economic development especially for developing countries since it provides: a substantial financial resource; an opportunity to transfer technological, organizational and managerial practices and skills; and access to international markets (Shatz and Venables, 2000; Alfaro et al., 2004). MNEs have played an essential role in shaping the patterns of economic development through their FDI decisions (McCann and Mudambi, 2004). Since the 1997 global economic crisis, many developing countries have primarily relied upon FDI inflow for economic/infrastructural development on a sustainable basis. Infrastructure development is widely considered as a crucial factor influencing the desirability of investment location, particularly for developing economies, such as Ghana. However, few studies have examined the effect of FDI inflows on infrastructure development. For instance, Frimpong and Oteng-Abayie, (2007) studied the causal link between FDI and GDP growth for Ghana for the pre- and post-Structural Adjustment Program (SAP) periods. In other developing economies Lipsey and Sjoholm (2011) studied the relationship between growth and FDI in East Asian countries. Moreover, Takii (2005) discussed the role of FDI by examining productivity spillovers from foreign multinational plants; and Takii (2011) examined the effect of FDI on economic growth in relation to the origin of investors in Indonesian manufacturing. Despite the growing importance of FDI inflows in developing economies, empirical evidence is limited on the determinants of location choice of FDI inflows at their regional level.

**Research method**

The study uses annual time series data covering the period 1984-2013 (based on the availability of data). Data sets were obtained from the World Bank (African Development Indicators Database); the Ministry of Finance and Economic Planning (Fiscal Data); and the Institute of Statistical, Social and Economic Research (ISSER) and Centre for Policy Analysis (CEPA) publications. All variables are in constant prices. The estimation procedures are undertaken with the aid of Stata 12 and Eviews 8 software packages. A two-stage least squares estimation method was adopted where FDI was endogenized; this approach enables any simultaneity issues to be overcome (c.f. Mansouri, 2005; Omoniyi and Omobitan, 2011). The model considers the impact of Infrastructure on FDI inflows in Ghana and is formulated as:

$$\ln FDI = \beta_0 + \beta_1 \ln Infra_{t-1} + \epsilon$$  

Where Infra is the log of infrastructure, FDI represents the log of FDI inflows and $\epsilon$ represents the error term.

**Unit root test**

Macroeconomic variables usually have a time dependent moment (non-stationary) which poses problems in the estimation results as the standard assumptions for
asymptotic analysis would not be valid. Consequently, estimating with ordinary least squares in the presence of non-stationary variables will lead to spurious results. Testing whether a given set of macroeconomic variables is stationary or not in time series analysis is critical to establishing model validity. Econometricians suggest the use of standard time-series unit root tests such as the Augmented Dicky Fuller test, Phillips-Perron and Dickey-Fuller test with Generalized Least Squares Detrending (DF-GLS) to check the stationarity of variables (Baum, 2000). The study uses the DF-GLS test as it is far more robust than alternative/complementary tests available. The DF-GLS is computed as follows:

\[ \Delta X'_t = \beta + \rho t + \delta X'_{t-1} + \sum_{v=1}^{p} \gamma_v \Delta X'_{t-v} + \]

where:
- \( X'_t \) = the detrended series;
- \( t \) = the time trend \( \beta \);
- \( \delta \) and \( \Delta \) = the constant or drift parameter (an arbitrary parameter and the first-difference operator respectively); and
- \( \gamma_v \) = the coefficients of the lagged difference terms and is an error term.

The null and the alternate hypothesis for the presence of unit root in the variable \( X_t \) for the DF-GLS tests are:

\[ H_0 : \delta = 0 \quad \text{(stationary)} \]
\[ H_1 : \delta < 0 \quad \text{(non-stationary)} \]

Rejecting the null hypothesis leads to the conclusion that the variable is not stationary and autocorrelation exists which will produce inaccurate estimates and incorrect inference generation. The presence of ARCH effects requires the use of lagged variables to achieve stationarity. To determine the optimal lag length (k), the Akaike Information Criterion (AIC) and Schwarz-Bayesian Criterion (SBC) are widely used.

**Model estimation and analysis**

The economic variables included in the model are: growth rate per capita GDP (gdppc) and population size (pop) which are proxies for market size; inflation (inf), measured as yearly percentage change in consumer prices and GDP growth (grw) – as proxies for economic stability; net exports (nx) – proxy for openness; and M2 as a percentage of GDP (Mg), – proxy for financial development and exchange rate volatility – measured as the variance of the US/GHS exchange rate around it mean – proxy for risk. Descriptive analysis of the observed variables below illustrates that annual change in the macroeconomic over the sample period (1984-2013) has been is very high. For example, net inflows of FDI over the sample period is averaging at 18.4 per cent annually with a standard deviation of 2.302 per cent and growth of electricity consumption increases by 5.7 percentage points annually (refer to Table I). A similar trend is apparent for the real effective exchange rate over the sample period. Growth in GDP has been changing annually at
approximately 1.522 per cent which is circa half of the annual change in inflation rate and trade openness.

Unit root test results
Stationarity tests were performed on the annualized log difference of variables using augmented Dickey–Fuller test. Tests were performed on both constant and constant with trend at 1 per cent, 5 per cent and 10 per cent levels of significance. Table II illustrates that inflation rate, GDP growth and electricity consumption were stationary at levels, indicating that there is no unit root at first difference with constant. However, FDI and real effective exchange rate (REEXR) were both found to possess a unit root at first difference with constant but when detrended, results reveal that the two series are stationary.

Figure 1 provides a graphical illustration of all the variables including FDI and real exchange rate after detrending. All variables illustrate little evidence of trend or drift at first difference. Having determined that the null hypothesis of non-stationarity at levels cannot be accepted, the cointegration of the variables is explored.

Test of cointegration
Since all the variables are first difference stationary, it was prudent to check for cointegration among the variables. The Johansen’s cointegration test was consequently performed using a maximum lag of 4. Results indicate (Table III) that there are at least 3

<table>
<thead>
<tr>
<th>Variables</th>
<th>N</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln FDI</td>
<td>39</td>
<td>18.386</td>
<td>18.483</td>
<td>2.3017</td>
<td>0.1801</td>
<td>1.933337</td>
</tr>
<tr>
<td>Ln Electricity</td>
<td>43</td>
<td>5.7303</td>
<td>5.8112</td>
<td>0.2891</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln GDP</td>
<td>42</td>
<td>1.5219</td>
<td>1.5789</td>
<td>0.6523</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ln inflation</td>
<td>49</td>
<td>3.0547</td>
<td>2.8975</td>
<td>0.7820</td>
<td>0.3417</td>
<td>3.010716</td>
</tr>
<tr>
<td>Ln REEXR</td>
<td>36</td>
<td>5.1396</td>
<td>4.8097</td>
<td>0.9642</td>
<td>1.8996</td>
<td>5.713947</td>
</tr>
<tr>
<td>Ln Openness</td>
<td>50</td>
<td>3.8409</td>
<td>3.8053</td>
<td>0.6583</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: *, ** and *** denotes significant at 1, 5 and 10 per cent
cointegrating ranks among the variables. The associated trace statistic of 42.5303 reveals that the null hypothesis of 'no cointegration among the variables' must be strongly rejected.

Results in Table IV illustrate that all models normalized on ln_FDI, ln_Electricity, ln_GDP and ln_REEXR were statistically significant; thus, the null hypothesis of "no long run relationship" is rejected.

Primary attention is given to lnFDI and lnElectricity as the operational models. Since a long-run cointegration relationship is established using the two models, it can be implied that FDI net inflows has a long run relationship with annualized electricity consumption (as proxy measure for infrastructure).

---

**Figure 1.**
Time series plot of variables

---

<table>
<thead>
<tr>
<th>Maximum rank</th>
<th>LL</th>
<th>Eigenvalue</th>
<th>Trace statistic</th>
<th>5% critical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>36.084425</td>
<td>0.77881</td>
<td>116.9669</td>
<td>94.15</td>
</tr>
<tr>
<td>1</td>
<td>57.206585</td>
<td>0.68328</td>
<td>74.7225</td>
<td>68.52</td>
</tr>
<tr>
<td>2</td>
<td>73.302725</td>
<td>0.50794</td>
<td>42.5303*</td>
<td>47.21</td>
</tr>
<tr>
<td>3</td>
<td>83.23091</td>
<td>0.34277</td>
<td>22.6739</td>
<td>29.68</td>
</tr>
<tr>
<td>4</td>
<td>89.107063</td>
<td>0.06492</td>
<td>10.9216</td>
<td>15.41</td>
</tr>
<tr>
<td>5</td>
<td>93.628073</td>
<td>0.06492</td>
<td>1.8796</td>
<td>3.76</td>
</tr>
<tr>
<td>6</td>
<td>94.567856</td>
<td>0.06492</td>
<td>1.8796</td>
<td>3.76</td>
</tr>
</tbody>
</table>

**Table III.**
Johansen’s cointegration rank test

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Chi Square</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>LnFDI</td>
<td>(lnElectricity, lnGDP, ln_Infl, ln_REEXR, lnOpen)</td>
<td>16.8417**</td>
</tr>
<tr>
<td>lnElectricity</td>
<td>(LnFDI, lnGDP, ln_Infl, ln_REEXR, lnOpen)</td>
<td>16.68719**</td>
</tr>
<tr>
<td>lnGDP</td>
<td>(lnElectricity, LnFDI, ln_Infl, ln_REEXR, lnOpen)</td>
<td>37.37948***</td>
</tr>
<tr>
<td>ln_Infl</td>
<td>(lnElectricity, lnFDI, LnGDP, ln_REEXR, lnOpen)</td>
<td>14.1797</td>
</tr>
<tr>
<td>ln_REEXR</td>
<td>(lnElectricity, lnGDP, ln_Infl, LnFDI, lnOpen)</td>
<td>62.93604***</td>
</tr>
<tr>
<td>lnOpen</td>
<td>(lnElectricity, lnGDP, ln_Infl, ln_REEXR, LnFDI)</td>
<td>13.56206</td>
</tr>
</tbody>
</table>

---

**Table IV.**
Johansen VECM models for cointegration tests
Determinants of foreign direct inflows

Given the observance of cointegration between variables, the determinants of FDI were estimated using cointegration regression estimators; specifically the Fully Modified OLS (FMOLS) and Conical Cointegration Regression (CCR) techniques. These methodologies provide a check for the robustness of results and have the ability to produce reliable estimates in small sample sizes. Results reproduced in Table V indicate that the estimates of the FMOLS and the CCR were very consistent and comparable indicating that the results were reliable. It is also revealed that electricity consumption and years have a positive and significant relationship on FDI. The coefficient of electricity consumption $B = 1.380$, $p < 1$ per cent in the FMOLS indicates that any 10 per cent increase in electricity demand will generate a circa 13.8 per cent increase in inflows of FDI. The same percentage reduction in electricity consumption causes a 13.7 per cent improvement in inflows per the CCR estimation. Similarly, results on year indicate that FDI inflows have been growing at a yearly rate of 0.3 per cent per annum.

In contrast, a negative and significant relationship was found to exist between FDI and GDP, and FDI and openness. This result is interesting because intuitively, one would suspect that openness of the economy to international trade would lead to an increase in FDI – this therefore confirms the tariff-jumping hypothesis is evident in Ghana. The results show that a 10 per cent openness in international trade through a reduction of import tariffs will lead to a 15.6 reduction in FDI according to the FMOLS model or a 15.5 per cent reduction in FDI according to the CCR model. It is clear that GDP growth has a long run negative relationship with FDI inflows. Specifically a 10 per cent increase in GDP growth will induce at least a 40 per cent reduction in FDI inflows based on the two models’ estimates. This suggests that the “market stealing” effect associated with increased FDI is apparent in Ghana, where MNCs push out domestic firms without FDI out of the market. The model’s explanatory power using the adjusted $R^2$ is validated at around 90 per cent for the fully modified OLS model and 87 per cent for the CCR.

Granger causality tests

Based on evidence that a long run relationship exists between electricity consumption and FDI, the short run relationship between the two variables was then investigated. To

<table>
<thead>
<tr>
<th>Model parameters</th>
<th>FMOLS Standard</th>
<th>Error</th>
<th>CCR Standard</th>
<th>Error</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln_gdp</td>
<td>-0.431*</td>
<td>0.194</td>
<td>-0.408*</td>
<td>0.172</td>
<td>Negative and significant</td>
</tr>
<tr>
<td>ln_REEXR</td>
<td>-0.00749</td>
<td>0.334</td>
<td>0.0172</td>
<td>0.298</td>
<td>No relationship</td>
</tr>
<tr>
<td>ln_inflation</td>
<td>0.169</td>
<td>0.104</td>
<td>0.190</td>
<td>0.167</td>
<td>No relationship</td>
</tr>
<tr>
<td>ln_openness</td>
<td>-1.562****</td>
<td>0.231</td>
<td>-1.546****</td>
<td>0.261</td>
<td>Negative and significant</td>
</tr>
<tr>
<td>ln_electricity</td>
<td>1.380***</td>
<td>0.232</td>
<td>1.367***</td>
<td>0.254</td>
<td>Positive and significant</td>
</tr>
<tr>
<td>year</td>
<td>0.299***</td>
<td>0.0158</td>
<td>0.296***</td>
<td>0.0122</td>
<td>Positive and significant</td>
</tr>
<tr>
<td>Constant</td>
<td>-580.1****</td>
<td>30</td>
<td>-581.2****</td>
<td>30</td>
<td>Negative and significant</td>
</tr>
<tr>
<td>Observations</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.907</td>
<td></td>
<td>0.874</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted $R^2$</td>
<td>0.883</td>
<td></td>
<td>0.842</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Standard errors in parentheses; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
determine the short run causal relationship between the two variables, the Granger Causality test was performed. Results indicated that there is strong evidence to support that growth in FDI net inflows helps to predict electricity consumption ($p$-value is 0.003 seems like an odd $p$-value); however, the growth in electricity demand does not cause the growth in FDI net inflows. Thus there is a uni-directional causal relationship between FDI net inflows and electricity consumption (Table VI).

Vector autoregression analysis to forecast foreign direct investment and electricity consumption

To assess the behavior of both FDI and electricity consumption (and forecast and conduct an impulse response analysis), VAR analysis was performed (Table VII). The optimal lag length of 1 was selected minimum values of AIC, Hannan and Quinn information criterion (HQIC), final prediction error (FPE) and Schwarz’s Bayesian information criterion (SBIC) criteria.

The VAR analysis was conducted with ln_FDI and ln_Electricity as dependent variables; remaining variables were exogenous variables based upon a cointegration relationship. The validity of the VAR was checked for stability and autocorrelation and it was observed that none of the eigenvalues were close to unity – thus all shocks will die out with time. Table VIII reveals that all the eigenvalues were inside the unit circle and so VAR stability was confirmed.

Because the null hypothesis of no residual autocorrelation at all lag orders cannot be rejected at any significance level, there is no evidence to contradict the validity of the VAR models specified and forecasting can be performed. Figure 2 illustrates that electricity consumption (Table VI).

<table>
<thead>
<tr>
<th>Model parameters</th>
<th>Excluded</th>
<th>Chi-square</th>
<th>df</th>
<th>Prob &gt; chi^2</th>
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</thead>
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<tr>
<td>Ln_FDI</td>
<td>Ln_Electricity</td>
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<td>0.580</td>
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<tr>
<td>Ln_FDI</td>
<td>All</td>
<td>0.30591</td>
<td>1</td>
<td>0.580</td>
</tr>
<tr>
<td>Ln_Electricity</td>
<td>Ln_FDI</td>
<td>8.7423</td>
<td>1</td>
<td>0.003</td>
</tr>
<tr>
<td>Ln_Electricity</td>
<td>All</td>
<td>8.7423</td>
<td>1</td>
<td>0.003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>lag</th>
<th>LL</th>
<th>LR</th>
<th>df</th>
<th>$p$</th>
<th>FPE</th>
<th>AIC</th>
<th>HQIC</th>
<th>SBIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-19.3796</td>
<td>51.465*</td>
<td>4</td>
<td>0.000</td>
<td>0.012304*</td>
<td>1.3082*</td>
<td>1.5497*</td>
<td>2.05711*</td>
</tr>
<tr>
<td>1</td>
<td>-3.64708</td>
<td>7.7975</td>
<td>4</td>
<td>0.099</td>
<td>0.013484</td>
<td>1.31659</td>
<td>1.61539</td>
<td>2.25069</td>
</tr>
<tr>
<td>2</td>
<td>1.56543</td>
<td>2.6275</td>
<td>4</td>
<td>0.622</td>
<td>0.016821</td>
<td>1.49564</td>
<td>1.85424</td>
<td>2.6166</td>
</tr>
<tr>
<td>3</td>
<td>3.21259</td>
<td>3.2943</td>
<td>4</td>
<td>0.510</td>
<td>0.020927</td>
<td>1.65249</td>
<td>2.07087</td>
<td>2.96028</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Eigenvalue stability condition</th>
<th>Modulus</th>
<th>Lag</th>
<th>Lagrange–multiplier test</th>
<th>Prob &gt; chi^2</th>
</tr>
</thead>
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<tr>
<td>VAR Stability and autocorrelation tests</td>
<td>0.7683365</td>
<td>1</td>
<td>3.0804</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>0.2481047</td>
<td>2</td>
<td>1.0728</td>
<td>4</td>
</tr>
</tbody>
</table>
consumption is predicted to decline whereas net inflows of FDI are predicted to rise towards its steady path.

**Effect of structural shocks on foreign direct investment and infrastructure**

In order to identify the effect of shocks to FDI on electricity consumption (and vice versa), impulse response analysis was conducted. Because the Granger causality test generally supported a growth in FDI and electricity consumption, the study specifically chose this approach to examine the effect of FDI growth on electricity demand. Figure 3 illustrates that the diagonal panels show the effect of shocks to FDI and electricity consumption to its own growth path in the future. In both cases the shocks die out gradually confirming the stationarity of the variables.

A one-standard deviation shock to electricity consumption in the top left of Figure 4 is slightly below 0.2 per cent whereas a similar jump to the growth FDI net inflows is in excess of 0.4 per cent. The top right and the bottom left panels show the effect of a shock to one variable on the other. At the bottom left of Figure 4 it is observed that a one-standard deviation shock to FDI raises electricity consumption steadily for the next six months but by the year-end unto the second year it attains a steady state. The top right panel, illustrates the effect of shocks to electricity consumption on FDI. A small dynamic effect is apparent that over a six months period which was to be expected. The variance decomposition results (Figure 4) indicates the extent to which each shock contributes to unexplained movements (forecast errors) in each variable.

For instance, the left-column panels reveal that the electricity consumption shocks contribute 100 per cent of the variance in the one-period-ahead forecast error for electricity consumption demand. However, after the forecast horizon moves further into the next 6 months, the effect FDI inflows will be felt as the contributions converged to approximately 80 per cent of variation in electricity demand. This is due to the electricity demand shocks and 20 per cent due to the FDI shock. The right-column panels indicate that 5 per cent of the variation in FDI is attributable to electricity consumption growth shocks in the short run or long run.
Figure 3. Impulse response

Source: NB: Impulse response assuming that the VAR residuals are uncorrelated

Figure 4. Plots forecast error variance decomposition
Conclusion
Based upon the study context and proxies used for infrastructure and growth, it can be concluded that there is positive and significant relationship between FDI and infrastructure development. The coefficient of electricity consumption $B = 1.380$, $p < 1$ per cent in the FMOLS indicates that a 10 per cent increase in electricity demand generates circa 13.8 per cent increase in inflows of FDI. The same percentage point reduction in electricity consumption results in a 13.7 per cent improvement in inflows per the CCR estimation. There was however a negative but significant relationship between FDI and GDP, and FDI and openness. This result supports the tariff-jumping hypothesis which states that foreign firms which seek to serve local markets may establish subsidiaries in the host country if it is difficult to import their products to that country. The study also concludes that 10 per cent openness in the country’s international trade either through reduction of import tariffs would lead to a 15.6 per cent reduction in FDI according to the FMOLS model or a 15.5 per cent reduction in FDI according to the CCR model. The results illustrate that GDP growth has a long run negative relationship with FDI inflows. Specifically a 10 per cent increase in GDP growth would induce at least a 40 per cent reduction in FDI inflows based on the two models' estimates. Finally, a 0.2 per cent shock to electricity consumption would result in a similar jump to the growth of FDI net inflows is in excess of 0.4 per cent. Moreover, a one-standard deviation shock to FDI raises electricity consumption steadily for the next six months but by the year-end into the second year, it attains a steady state.

Based upon these findings, it is recommended that managers of the country’s economy should prioritize specific areas that require FDI. Incentives should be available to attract investments in such sectors. It is also important that areas prioritized are related and support local industries. Even though trade theorists encourage countries to engage in trade, care must be taken not to excessively open the country’s market for exploitation without some trade restrictions to promote growth of local firms. To attract more FDI, governments need to commit additional resources towards infrastructure development particularly within the energy sector. This was evident in the study which indicates that any 10 per cent increase in electricity infrastructure generates about 13.8 per cent increase in inflows to FDI. This is because energy forms the backbone of every economy; therefore, infrastructure investments bring about long lasting solutions to the country’s perennial energy challenges.

References


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The role of knowledge sharing in supply chain success

Literature review, classification and current trends

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Abstract

Purpose – The aim of this paper is to provide a comprehensive and detailed review of the state-of-the-art mechanisms of knowledge sharing (KS) in the supply chain (SC) field, as well as directions for future research. Briefly, this paper tries to offer a systematic and methodical review of the KS mechanisms in the SC to provide a comparative summary of the selected articles, to collect and describe the factors that have the influence on KS and SC, to explore some main challenges in this field and to present the guidelines to face the existing challenges and outlining the key areas where the KS mechanisms in SC can be improved.

Design/methodology/approach – In the current study, a systematic literature review up to 2018 is presented on the supply chain’s mechanisms of KS. The authors identified 21,907 papers, which are reduced to 25 primary studies through the paper-selection process.

Findings – The results showed that the KS in SC helps to increase the success of the organizations, improve employee performance, increase competitive advantage, enhance innovation and improve relationships between supplier and consumer. However, there were some weaknesses, such as staff resistance to share knowledge in the SC because of fear of job loss.

Research limitations/implications – There are several limitations to this study. This study limited the search to Google Scholar. There might be other academic journals where Google does not find their paper and they can offer a more complete picture of the related articles. Finally, non-English publications were omitted from this study. It is possible that the research about the application of KS in SC can also be published in other languages. In addition, more studies need to be carried out using other methodologies such as interviews.

Originality/value – The paper presents a comprehensive structured literature review of the articles’ mechanisms of KS in SC. The paper’s findings can offer insights into future research needs. By providing
comparative information and analyzing the current developments in this area, this paper will directly support academics and practicing professionals for better knowing the progress in KS mechanisms.

**Keywords**  Supply chain, Knowledge management, Knowledge sharing, Systematic literature review

**Paper type**  Literature review

1. **Introduction**

Researchers have recently concluded that effective organizations are those who can create and distribute the knowledge rapidly and can use the created knowledge for designing new products for consumers (Liu *et al.*, 2017; Madan, 2015; Nonaka, 2008). Knowledge is regarded as a key component for organizational innovation and it is a vital asset for enabling the organizations to gain a competitive advantage (López-Nicolás and Meroño-Cerdán, 2011; Marra *et al.*, 2016). Improving the techniques for how the knowledge can be captured and shared among the entities of companies is gained much attention (Gao and Bernard, 2018; Movahedipour *et al.*, 2018). Knowledge sharing (KS) is considered as a key aspect for organizations to get a competitive gain (Al-Hawamdeh, 2003; Navimipour and Charband, 2016). KS is about the providing of know-how to help others and to cooperate with them to solve problems, improve new thoughts, or implement strategies and actions (Ahmed *et al.*, 2018; Olson, 2015; Wang and Noe, 2010).

On the other hand, firms attempt to realize more supply chain (SC) collaborative innovation to enhance the knowledge of their partners (Ulhaq *et al.*, 2017; Wang and Hu, 2016). In SC systems, used products might re-enter to the SC process at anywhere (Nagurney, 2006; Taher *et al.*, 2016). In such a complicated system, the acceptance, making, storage, transmission, sharing and application of knowledge management (KM) is the preferred response to the new challenges of the SC (Cerchione and Esposito, 2016; Lim *et al.*, 2017). A relational risk is negatively associated with a desire for sharing of knowledge between partners, which causes a negative effect on KS (Cheng, 2011; Todo *et al.*, 2016). The relationship and institutional orientation play a vital role in ensuring the inter-organizational KS (Cheng and Fu, 2013; Kumar and Rajan, 2019).

However, despite the effect of the KS on the success of SC, as far as we know, the comprehensive and systematic study about the role of KS mechanisms in SC is very rare. Thus, the purpose of this paper is to examine the role of KS mechanisms in SC and to define the types of important challenges. Besides, we suggest some directions for future studies. Briefly, the objectives of the paper are:

- offering the systematic and methodical review of the KS mechanisms in the SC;
- offering a comparative summary of the selected articles;
- collecting and describing the factors that have the influence in KS and SC;
- exploring some main challenges in this field and presenting the guidelines to face the existing challenges; and
- outlining the key areas where the KS mechanisms in SC can be improved.

The related work is summarized in the next section. Section 3 introduces the backgrounds. Section 4 discusses the paper selection process. In Section 5, the reviewing of selected papers is presented. Results and comparison are discussed in Section 6. In Section 7, open issues are discussed. Also, we will conclude the paper in the last section. Finally, the commonly used abbreviations are shown in Appendix.
2. Related work

Some review papers about KS and SC are discussed in this section to highlight our motivation for writing this paper.

Tolooie and Soleimanynanadegany (2011) have reviewed the role of KM in SC Management (SCM). In addition, they have planned a model linking knowledge development to cycle time in strategic SC. So, the ability to create, acquire, mix and deploy distributed knowledge has emerged as a vital organizational ability. The paper recognizes that there is hardly any prove available on the collaboration enhancing between company’s outcome and IT strategies. The essay discusses building theories and empiric way of investigation. The disadvantages of this article are:

- The article selection method is not clear in the articles.
- There is not any logical classification of the papers.
- The articles are not compared comprehensively.
- Their organization does not have systematic validation.
- Advantages and disadvantages of the articles have not been discussed.

Marra et al. (2012) have investigated the role of KM in SCM by studying the available literature. This review recognizes various theoretical and methodological features in which KM applications are applied in the SC context. The review shows that there is little indication of the positive relationship between IT usage and firms’ performance. They have reviewed relevant articles from 2000 to 2010. However, the collection of articles has not been done systematically. There is also no classification and comparison of articles. The disadvantages of this article are:

- There is not any logical classification of the papers.
- The comparing among articles are not provided.
- The focus of the paper is only on SCM.
- There is a limitation on the collection of relevant articles.

Also, Shenghua (2013) has examined the review of researches on influencing factors of KS based on SC. He has summarized the results of research on influencing factors of inter-organizational KS from the perspective of SC. He also reviewed the viewpoints in the research on influencing factors of KS in the SC from 4 aspects, that is sharing subject, sharing an object, sharing a channel, and sharing context. Finally, he has summed up the current researches and points out some localized research directions. However, the disadvantages of this article are:

- The paper is written in a non-systematically way.
- The paper selection process is unclear.
- The discussed articles have not been classified and compared.

Outahar et al. (2013) have reviewed and analyzed existing contributions in implementing KM in SC. The paper summarized several theoretical and methodological characteristics that have been developed recently to highlight the way in which KM applications are proposed in the SC context. In particular, the paper focuses on three areas of research: Knowledge transfer, KS and knowledge creation, and learning. The combined KM and SC literature reviewed allow recognizing that many of the KM concepts are pertinent to SCM. Consequently, more and more companies are starting to realize and subsequently reap the benefits of KM adoption and implementation within their SC. The disadvantages of this article are:
The selection process of articles is vague.
The comparing among articles is not provided.
Newly published articles have not been discussed.

Furthermore, Rui and Wu-yi (2015) have studied a detailed review on the researches of KS in SC from following aspects, competitive advantage, technical support, factors, sharing mechanism, products, evaluating indicator, and analyzed the deficiencies. They also have offered research paths for the future. The main result is that enterprises can gain a competitive advantage form KS in SC. The disadvantages of this article are:

- The articles selection process is not clear.
- The articles are not compared in details.
- The tabular comparisons of the reviewed papers are missed.

Furthermore, Cerchione and Esposito (2016) have provided a review of KM in SC to recognize the state-of-the-art literature to describe suitable research questions. The results have shown that though there are many papers addressing KM in SC, many research questions are still ignored. Particularly, the paper highlights eight main gaps in the SC literature. From these gaps, nine research questions have been described. However, the disadvantages of this article are:

- Advantages and disadvantages of the articles have not been discussed.
- The literature review is limited to the years 1960-2015.

del Rosario Pérez-Salazar et al. (2017) have surveyed the KM and SCM research via forming three standpoints, methodological approach, SCM area, and KM processes. The results have shown that KM can be viewed as a leverage mechanism for SC integration, SC approach alignment; the improvement of inter and intra-relations across the SC; and the reinforcement of knowledge transfer in product development. Also, they have shown that some SCM areas such as reverse logistics, inventory management, request planning, outsourcing, and risk assessment are explored slightly. The drawbacks of this study are:

- Newly published articles have not been discussed.
- The comparing among articles is not provided.
- There is not any logical classification of the papers.

Based on the discussed articles in this section, we found that different topics in this domain are the factors of inter-organizational KS from the perspective of SC, the competitive advantage, technical support, factors, sharing mechanism, products, evaluating indicator, and the deficiencies, SC approach alignment. Some review research has been done in the domain of KS and SC. However, there have been few reviews on this topic, also, KS benefits in SC have not been discussed well. While systematic reviews are very important for performing a sound review (Ghanbari et al., 2019; Shabestari et al., 2019), these surveys did not present a complete Systematic Literature Review (SLR)-based review of the KS application in the SC with an analysis of their taxonomy and future challenges. Table I provides a brief summary of the reviewed surveys and their main properties. As shown in Table I, the most weakness in the examined articles is lacking the articles selection process. In addition, many articles are not provided the logical classification. In addition to the aforementioned, articles comparison, and their analysis in detail are the other important weaknesses. Therefore,
<table>
<thead>
<tr>
<th>Article</th>
<th>Main idea</th>
<th>Advantage</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolooie and Soleimanynanadegany (2011)</td>
<td>Examining the review on the role of KM in SCM</td>
<td>Providing a model linking knowledge development in strategic SC, Discussing the ability to create, obtain, integrate, and organize distributed knowledge</td>
<td>The article selection method is not clear in the articles, There is not any logical classification of the papers, The articles are not compared to comprehensively, Their organization does not have systematic validation, Advantages and disadvantages of the articles have not been discussed</td>
</tr>
<tr>
<td>Marra et al. (2012)</td>
<td>Investigating the role of KM in SCM</td>
<td>The review recognizes various theoretical and methodological features in which KM applications are applied in the SC context</td>
<td>There is not any logical classification of the papers, The comparing among articles is not provided, The focus of the paper is only on SCM, There is a limitation on the collection of relevant articles</td>
</tr>
<tr>
<td>Shenghua (2013)</td>
<td>Examining the review of researches on influencing factors of KS based on SC</td>
<td>Discussing the sharing subject, sharing an object, sharing a channel, and sharing context</td>
<td>The paper is not a systematical survey, The paper selection process is unclear, The discussed articles have not been classified and compared</td>
</tr>
<tr>
<td>Outahar et al. (2013)</td>
<td>Implementing KM in SC</td>
<td>Grouping the factors of inter-organizational KS from the perspective of SC</td>
<td>The selection process of articles is vague, The comparing among articles are not provided, Newly published articles have not been discussed</td>
</tr>
<tr>
<td>Rui and Wu-yi (2015)</td>
<td>The studying a detailed review of the researches of KS in SC</td>
<td>Focusing on three areas: Knowledge transfer, KS and knowledge creation, and learning</td>
<td>The papers analyzing the competitive advantage, technical support, factors, sharing mechanism, products, evaluating indicator, and the deficiencies</td>
</tr>
<tr>
<td>Cerchione and Esposito (2016)</td>
<td>Providing a review of KM in SC to identify the state-of-the-art literature</td>
<td>Discussing the research gaps</td>
<td>Advantages and disadvantages of the articles have not been discussed</td>
</tr>
<tr>
<td>del Rosario Pérez-Salazar et al. (2017)</td>
<td>Grouping the KM and SCM research via forming three standpoints, methodological approach, SCM area, and KM processes</td>
<td>Showing that KM viewed as a leverage mechanism for SC integration, SC approach alignment, The improvement of inter and intra-relations across the SC, The reinforcement of knowledge transfer in product development</td>
<td>The literature review is limited to the years 1960-2015</td>
</tr>
</tbody>
</table>

Table 1. Comparison of discussed articles about KS systems on SC success
in the rest of this paper, we try to solve the mentioned issues and provide an up-to-date analytical review paper in this domain.

3. Background
In this section, the articles related to the role KS in SC success have been divided into three major categories (strategic, operational and managerial benefits) according to Figure 1.

3.1 Strategic benefits
Over the past decades, SCM has been a vital and strategic mechanism for organizations to reach a good competitive advantage. There have been many changes in SC activities since the 1960s, most of which are about technological development (Ardito et al., 2018; Chou et al., 2004). An important issue in the SC strategy is that an organization cannot compete singly and succeed in today’s market. Hence, many organizations try to coordinate inter-organizational activities with each other to achieve individual and collective performance (Matopoulos et al., 2007). For this purpose, knowledge, and information sharing through collaborative, activates facilitates market access, reinforces competitive position, increases market share and improves the worth of the company (Clemons and Slotnick, 2016; L. Li, 2012). Also, collaboration can increase the value-add of a company by reducing the time it takes to market the product, reducing its distribution time, and improving its quality (Matopoulos et al., 2007; Rodriguez-Enriquez et al., 2016).

3.2 Managerial benefits
Managerial benefits rise from planning problems that are related to the medium term (Huang et al., 2003). Production planning, which involves improving product quality, minimizing supply discontinuity, is one of the key points in a management plan. Correct planning in distribution (faster delivery, increased flexibility in delivery) can lead to more profit (Matopoulos et al., 2007; Ryoo and Kim, 2015). Managers are trying to use SC processes to improve performance. They should focus on recognizing the current and future SC needs of customers and then makes an effective process to meet those requirements (Khodaei et al., 2018; Stank et al., 2001). Communication strategies were recommended as a competitive key in SCM. Communication between buyers and sellers is a key advantage to the SCM (Ellinger et al., 1999). The flow of information through collaborative networks enables firms to lessen information delay (Angerhofer and Angelides, 2006; Percin, 2008). So, to implement an efficient SCM, the businesses must found management practices governing their consistent performances and/or behaviors (Nasr et al., 2015; Vann, 2016).

3.3 Operational benefits
In general, operational benefits are related to daily events in an SC. Inventory, delivery time, cost, information, and planning are important for gaining operational benefits. Many organizations try to integrate the numerous elements of their SC for enhancing efficiency (Kannabiran and Sundar, 2011). Past research showed that manufacturers could enhance SC agility, decrease cycle time, reach higher efficiency, and deliver products in a timely way.

Figure 1. Categorization of the role of KS systems in the SC success

The role of KS systems in SC success
- Strategic benefits
- Managerial benefits
- Operational benefits
Consequently, organizations invest heavily in Information Technology (IT) to gain a competitive advantage in today’s highly dynamic business market (Kim and Kim, 2009). Also, increasing revenue and reducing costs is one of the things that help to strengthen the financial strength of the colleagues (National Research Council, 2000; Simchi-Levi et al., 2004).

4. Methodology

As the article reviewing via SLR is impartial, replicable, fair, systematic, complete, and clear, it can be considered as the first choice of articles reviewing methodology (Charband and Navimipour, 2016; Weed, 2005). Also, SLR in management can provide transparency clarity, accessibility, and fair comprehensive coverage on a specific managing area (Navimipour and Charband, 2016; Pittaway et al., 2005). Victor (2008) has defined SLR as a concept of identifying, assessing, and interpreting all available researches related to a specific research query or topic area (Ali et al., 2018; Charband and Navimipour, 2018). The approach of the current review involved extensive searches of relevant databases to identify all literature on KS and its role on SC success.

4.1 Question formalization

The current research aims at categorizing and examining all related studies that have examined the role of KS systems in the SC success. Another goal of this study is better understanding of the main issues in the field of SCM. The aims of this study are responding to the following questions:

Q1. What is the worth of KS systems in SC?
Q2. How is the searching for the article to understand the role of KS systems in the SC success?
Q3. What are the important components of KS systems that affect SC success?
Q4. What are the benefits and drawbacks of KS systems in SC?
Q5. What are the challenges and open issues of KS systems in SC?

4.2 Article-selection process

The article selection can be fulfilled in three steps. In step 1, Google Scholar, Emerald, Science Direct and ABI/Inform Global ProQuest are used as a key search engine to discover relevant articles based on some keywords including (knowledge sharing supply chain) or (supply chain) and (knowledge management supply chain). So, using automatically search process, 21528 articles are found from the journals, conferences, and books. Figure 2 shows the classification of the articles in each publisher. Finally, Figure 3 shows the distribution of the articles over time and Journals. In 2018, the published articles are highest.

Step 2 sets some criteria to assure those worthy publications are involved in the review. The editorial notes, working papers, review articles, reports and non-English papers are excluded. Finally, 989 articles are considered for detailed analysis. The published papers by famous publishers such as IEEE, Elsevier, Springer, Sage, Emerald, Taylor, ACM, Wiley and IGI are selected based on their title (Saberi, 2009). Also, citations of the paper are considered in this stage (Saberi and Ekhtiyari, 2019; Saberi et al., 2011).

In Step 3, to verify the relevance of the article, they are reviewed in detail. The subject, publication year, and rank of the journal are the key issues to decide the including or excluding of the articles. After applying these filters, the related articles are selected which
are published by nine famous publishers. So, 964 articles are excluded. Finally, 25 articles have remained which are certainly about the role KS systems in SC success, explained the proposed technique evidently and clearly, and improved some of the related parameters.

An overview of the used process for articles selection is illustrated in Figure 4. Also, the number of articles in each group shows in Figure 5. A summary of the applied process to classify the articles is illustrated in Table II. The searching process resulted in identifying 25 relevant articles for analysis (The 18 articles analyses in Section 5 and 7 articles analyses in section 2.). Also, Table III shows the classified papers.

5. Review of knowledge-sharing mechanisms in supply chain
The philosophy of SCM lies in the fact that the total performance of SC increases when the performance of each of the organizations is optimized. On the other hand, information is also considered as a determinant factor in increasing the productivity of complex organizations, which summarizes the ability of today’s organizations to process information and improve their speed in sharing and deciding (Breen and Crawford, 2005). In general, in an SC, the
performance or responsiveness of businesses related to the amount of shared information by companies. The greater the amount of shared information associated with product supply, customer demand, market forecasts, and production scheduling causes the responsiveness abilities of these companies (Bagal et al., 2018; Slone et al., 2007). Hence, in this section, we have divided the important factors of KS in the SC into three segments strategic, operational, and managerial benefits, and we have collected their key points.

5.1 Strategic benefits
Cheng (2011) has developed a conceptual model in which relational risk as a mediating construct to assess the interrelationship effects. Structural equation modeling (SEM) with Linear Structural Relations (LISREL) was analyzed the hypothesized relationships of the model. The results have shown that institutional orientation plays a serious role in confirming the inter-organizational KS. In addition, a relational benefit between green SC members improves the willingness of partners to develop their relationships to enhance KS. Inter-organizational KS is increasingly popular to managers because business relationships are improved to realize corporate goals (Im and Rai, 2008; Liu et al., 2012). However, it did not generalize to all forms of SC, as these findings only reflect the setting of Taiwan’s SC. Quantitative benefits of improving the SC performance are in many terms such as delivery performance, inventory reduction, fulfillment cycle time, forecast accuracy, productivity, lower SC costs, and fill rates.

Ajmal and Kristianto (2012) have examined KS in SC by developing analytical models to minimize KS uncertainty. Analogies from thermodynamics are used to describe the phenomenon in SC KS. The study funded that distance and sender capacity is important to reduce KS uncertainty. Furthermore, higher contact frequency between the sender and the receiver without considering sender capacity is proven to be

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**Table II.**

<table>
<thead>
<tr>
<th>Stage</th>
<th>The role of KS systems in SC success</th>
</tr>
</thead>
<tbody>
<tr>
<td>S 1</td>
<td>21,528 articles</td>
</tr>
<tr>
<td>S 2</td>
<td>Journals 13,165 articles</td>
</tr>
<tr>
<td></td>
<td>Conferences 8,542 articles</td>
</tr>
<tr>
<td>S 3</td>
<td>Books 25 articles</td>
</tr>
<tr>
<td>Details of selected articles in each stage</td>
<td>Until 2013 11 articles</td>
</tr>
</tbody>
</table>

**Figure 5.**

The number of articles in each group
insignificant to reduce uncertainty. The mechanism provides a new approach to explicate KS in supply networks. It also serves as a deep-rooted opening point for supplementary empirical assessment. The mechanism facilitates managers to expand their understanding of composite circumstances embedded into global supply networks to share their knowledge. With enhanced understanding, managers can spotlight their actions, increasing their firms’ competitiveness. This study provides a deeper theoretical understanding of KS in supply networks with a practical approach. However, the focus of the study is limited to one.

Liu et al. (2015) have analyzed the mechanism of KS between enterprises in SC collaborative innovation. Their paper analyzes the SC members’ willingness to KS based on game theory. Moreover, the result of KS between two companies is analyzed by employing the evolutionary game. They have broken the KS process in SC collaborative innovation into knowledge mining and transferring. In addition, the best KS strategy of each SC member

<table>
<thead>
<tr>
<th>Group</th>
<th>Year</th>
<th>Author</th>
<th>Publisher</th>
<th>Journal/Conference names</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategic benefits</td>
<td>2011</td>
<td>(Cheng)</td>
<td>Elsevier</td>
<td>Transportation Research Part E: Logistics and Transportation Review Decision Making Theories and Practices from Analysis to Strategy</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>(Ajmal and Kristianto)</td>
<td>IGI</td>
<td>journal of Industrial Engineering and Management</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>(L. Liu, Chen, and Niu)</td>
<td>JIEM</td>
<td>AJMI-ASEAN Journal of Management and Innovation</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>(Chuaynugul)</td>
<td>AJMI</td>
<td>AJMI-ASEAN Journal of Management and Innovation</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>(Q. Wang and Qiao)</td>
<td>IEEE</td>
<td>Internationa Journal of Logistics Management</td>
</tr>
<tr>
<td>Managerial benefits</td>
<td>2010</td>
<td>(C.-M. Huang, Su, and Chen)</td>
<td>Taylor and Francis</td>
<td>Journal of Statistics and Management Systems</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>(Cheng and Fu)</td>
<td>Elsevier</td>
<td>International Journal of Information Management</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>(Lin)</td>
<td>Emerald</td>
<td>The International Journal of Logistics Management</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>(Haque and Islam)</td>
<td>Emerald</td>
<td>Journal of Global Operations and Strategic Sourcing</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>(M. Gao and Ji)</td>
<td>IEEE</td>
<td>2018 Chinese Control And Decision Conference (CCDC) Management</td>
</tr>
<tr>
<td>Operational benefits</td>
<td>2010</td>
<td>(Rashed, Azeem, and Halim)</td>
<td>IOSCM</td>
<td>Journal of Operations and Supply Chain Management</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>(Shih, Hsu, Zhu, and Balasubramanian)</td>
<td>Elsevier</td>
<td>Information and Management</td>
</tr>
<tr>
<td></td>
<td>2014</td>
<td>(Singh and Power)</td>
<td>Taylor and Francis</td>
<td>International Journal of Production Research</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>(Tuan)</td>
<td>Taylor and Francis</td>
<td>International Journal of Logistics Research and Applications</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>(S.B. Grant and Preston)</td>
<td>Elsevier</td>
<td>Information and Management</td>
</tr>
</tbody>
</table>

Table III. Classification of selected papers in three main categories
The interaction among collaborative innovation capability, collaborative innovation activities, KS, and innovation performance in SC networks have been examined in Wang and Hu (2017). The 236 firms in China were investigated and the results have shown the positive relationships between KS, collaborative innovation activities, collaborative innovation ability, and innovation performance of a firm. Furthermore, it is expected that KS can play a fractional mediating role in the relationships between collaborative innovation activities and the firm’s innovation performance. However, the low sample size limited the obtained results.

Chuaynugul (2017) has examined how collaboration among SC firms mediates the relationship between inter-organizational trust and KS intention. The data was collected by a simple random sampling technique of 50 multinational organizations in Thailand and the USA. By using PLS regression analysis, the result showed that there was a positive relationship between inter-organizational trust and KS intention. The analysis also found that collaboration was the real mediator between inter-organizational trust and explicit KS intention. There are some limitations in conducting this research. Firstly, time limitation, all data was collected under cross-sectional designed, so the researcher conducted at one point in time. This may cause a high variance in the result. Secondly, the number of respondents is quite low (N = 50). Therefore, variances may happen and may link to wrong result interpretation. A final limitation is that their sample may not represent all global SC behaviors. At the result, there may cause some error by different cultures and geographic location. Moreover, the sample size should represent to entire SC population along with the globe.

Wang and Qiao (2018) have analyzed the effect of hitchhiking behavior in the process of KS in SC. Based on the evolutionary game theory, the basic game model of KS and the game model of incentive mechanism are recognized. The results have shown that the introduction of an incentive mechanism increases the probability of KS among enterprises in SC. In addition, the behavior of KS in SC is affected by other factors besides economic factors. In addition, this paper only considers the cost of KS and risk loss in economic factors.

Table IV provides an overview of the most important advantages and disadvantages of the KS strategic benefits mechanisms in SC. According to the reviewed studies in this section, the following benefits have been seen:

- facilitating SC collaboration;
- increasing market share;
- promoting value-added products;
- providing quick access to markets;
- increasing technological power;
- facilitating new product design development; and
- increasing speed to access knowledge.

5.2 Managerial benefits

Huang et al. (2010) have highlighted the importance of knowledge creation and sharing for SC practice. They have adopted 601 samples from top manufacturing firms based in 24 countries and performed SEM to test the hypotheses. They have examined the influence of alignment among knowledge creation and sharing, SC practices and competitive performance.
The results have indicated that manufacturers could perform very competitively when valuable knowledge has been created and shared and in turn can further influence and improve their SC practices. Through the influence of knowledge creation and sharing, effective SC practice can drive high performance. Using test results, they can prove that knowledge plays a key role in successful SC practices.

Cervellon and Wernerfelt (2012) have examined the knowledge content and the expectations regarding sustainable SC which is held by consumers. The results have indicated a change in knowledge content between two periods (2007-2008 and 2010-2011). The paper proposes an original viewpoint on the green fashion of SC and consumer vision of the industry, through the point of view of online communities. However, the use of information through electronic media by anonymous participants brings attendant problems such as limited information on participants' profiles. In addition, the paper suffers from the qualitative nature of the research.

Also, Cheng and Fu (2013) have developed a conceptual model for examining the interrelationship effects on KS. The results have suggested that the relationship orientation and institutional orientation play a critical role in ensuring the inter-organizational KS. The study improves a conceptual model that relational risk as a mediating variable examines the inter-relationship effects on the KS. They have analyzed the gathered data from 312 of the top 1,000 Taiwanese firms. The finding provided practical visions into how SC members should strengthen their relational and institutional view of relational governance and manage relational risks to develop collaborative behaviors. The research also provides multiple insights for managers and practices that look for inter-organizational knowledge improving in SC. However, findings could not generalize to all forms of SC.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Main idea</th>
<th>Advantages</th>
<th>Limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheng (2011)</td>
<td>Providing a model for evaluating a relational</td>
<td>Enhancing the inter-organizational KS</td>
<td>The findings reflect the setting of</td>
</tr>
<tr>
<td></td>
<td>risk as a mediating construct</td>
<td>Providing the competitive advantage of green SC</td>
<td>Taiwan’s SC only</td>
</tr>
<tr>
<td>Ajmal and Kristianto (2012)</td>
<td>Providing a new approach to explicate KS in</td>
<td>Minimizing KS uncertainty</td>
<td>The focus of the study is limited to</td>
</tr>
<tr>
<td></td>
<td>supply networks</td>
<td>Increasing firms' competitiveness</td>
<td>one area</td>
</tr>
<tr>
<td>Liu et al. (2015)</td>
<td>Examining the game analysis of the KS</td>
<td>Improving competitiveness</td>
<td>Sample size limit</td>
</tr>
<tr>
<td></td>
<td>mechanism for the SC</td>
<td>High innovation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>collaborative innovation</td>
<td>Helping KS in organizations</td>
<td></td>
</tr>
<tr>
<td>Wang and Hu (2017)</td>
<td>Evaluating the effects of collaborative</td>
<td>High innovation</td>
<td>Low sample size</td>
</tr>
<tr>
<td></td>
<td>innovation capability on innovation</td>
<td>performance in SC networks</td>
<td></td>
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<td></td>
<td></td>
<td>High-speed service</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>High the speed of new products</td>
<td></td>
</tr>
<tr>
<td>Chuaynugul (2017)</td>
<td>Evaluating the collaboration among business</td>
<td>Useful results for SC</td>
<td>Time limitation</td>
</tr>
<tr>
<td></td>
<td>SC firms on inter-organizational trust and KS</td>
<td>multinational companies</td>
<td>Low sample size</td>
</tr>
<tr>
<td></td>
<td>intention</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wang and Qiao (2018)</td>
<td>Studying the incentive mechanism of KS in SC</td>
<td>Improving the probability of KS between enterprises</td>
<td>Only considering the cost of KS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>in the SC</td>
<td>and risk loss in economic factors</td>
</tr>
</tbody>
</table>

The lack of communication between innovation and KS

Table IV. Side-by-side summarization and comparison of the most important advantages and disadvantages of the KS strategic benefits mechanisms in SC
Furthermore, Lin (2017) has revealed IT deployment capability, operational capability, human resource capability, and KS as the key antecedents of Electronic SCM (e-SCM) diffusion among Taiwanese firms, where higher levels of e-SCM diffusion cause higher competitive performance. Survey data from 142 managers of large Taiwanese firms were collected and used to evaluate the hypotheses employing hierarchical moderated regression analysis. The obtained results have shown that IT deployment capability, human resource capability, operational capability, and KS are significant antecedents of e-SCM diffusion. In turn, higher levels of e-SCM diffusion cause greater competitive performance. This study also finds that KS plays a moderating role by establishing the relationship between organizational capabilities and e-SCM diffusion. From the managerial viewpoint, the findings of this paper deliver decision guides for practitioners for improving the firm internal capabilities.

Gao and Ji (2018) have assessed the effect of relationship commitment on KS from SC enterprises. It also explored the mediating role of trust and reciprocity responsibility. They have used structural equation modeling based on 168 questionnaires from SC enterprises. The research results showed that the committed relationship of SC partners has a positive effect on KS, and can influence the KS behaviors of SC through reciprocity responsibility. The above conclusion leads enterprises to improve the KS among SC partners in the following two aspects. Their research has the following limitations. Firstly, there are some limitations in the sample size, and future research can expand the sample capacity to carry out more research that is extensive. Secondly, there is no empirical evidence for the hypothesis that this paper has not been verified and future research can redesign the measurement scale to solve the problem. Finally, the service-oriented SC has become the development trend, and the empirical studies or case studies can be used to confirm the application of the conclusions of this paper in KS of service-oriented SC.

Haque and Islam (2018) have investigated the relationships regarding the SC collaboration practices and KS with organizational performance in the pharmaceutical industry of a developing country. Structural equation modeling and factor analysis were applied to assess the research hypotheses. The findings have shown that both KS and collaboration practices in the SC effect customer satisfaction leading to business competitiveness as evidenced in the superior product quality and new product innovation. The findings of the paper have also shown the important practical implications because of the fact that the aspect of KS exerts an effect on customer satisfaction that holds the key to competing priorities. However, the study is performed only in the pharmaceutical industry from the viewpoint of a developing country.

Table V shows side-by-side summarization and comparison of the most important advantages and disadvantages of the discussed mechanisms. According to the reviewed studies in this section, the following benefits have been seen:

- increasing communication;
- increasing capacity allocation decision;
- cooperating among the members of the SC;
- making a better decision on predicting, planning, and supply control; and
- mutual sharing of information among the members of the SC.

5.3 Operational benefits
Rashed et al. (2010) have focused on the combined consequence of information and KS on supplier’s operational performance through supplier-buyer relationship. A conceptual
model was formulated based on previous literature. A questionnaire-based survey was performed. Data from 30 Bangladeshi Readymade Garments Industry were collected through interview and mail survey. Content validity, construct validity, and reliability is tested. Path analysis is performed for the identification of the validity of the model. The findings showed that information sharing is a prerequisite for KS and the close supplier-buyer relationship is a vital factor for escalating the supplier’s operational performance. However, this model has not been evaluated in the real environment.

Shih et al. (2012) have investigated the role of KS in SC. The results provided in the form of scenario-building and scenario-based simulation. They have offered a real-world case study of KM practice. Results have suggested that a viable KS mechanism, when blended with suitable KM strategies, could help bridge the separated gaps or separated SC partners with conflicting aims. This approach improves the effectiveness and productivity of the entire SC. It decreases the cycle time for moving services from manufacturers to customers. However, the research investigates only one firm.

Singh and Power (2014) have developed a framework by offering a firm-level operational concept related to innovative KM practices. They have confirmed this proposition by empirically analyzing the relationship between KS practices within and between trading partners and investigating the effect of these practices on firm performance. Data were gathered from 418 organizations in the manufacturing industry in Australia to measure the degree to which innovative KS practices provide a competitive benefit. The results have shown that three innovative KS constructs are strongly interrelated. However, the results cannot generalize.

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<tr>
<th>Paper</th>
<th>Main idea</th>
<th>Advantages</th>
<th>Limitation</th>
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<tbody>
<tr>
<td>Huang et al. (2010)</td>
<td>Highlighting the importance of knowledge creation and sharing for SC practice</td>
<td>High performance, Creating a competitive advantage</td>
<td>The study has not been implemented in the cluster environment</td>
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<tr>
<td>Cervellon and Wernerfelt (2012)</td>
<td>Reviewing the KS among green fashion communities online lessons for the sustainable SC</td>
<td>Highlighting the power of spreading information within the community, Sustaining the development of the industry</td>
<td>Limited information on participants’ profiles</td>
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<tr>
<td>Cheng and Fu (2013)</td>
<td>Providing a model for the examine the interrelationship effects KS</td>
<td>Improving inter-organizational knowledge in SC, Facilitating sustain competitive advantages</td>
<td>The results are not generalizable for all forms of SC</td>
</tr>
<tr>
<td>Lin (2017)</td>
<td>Developing a model that offers an understanding of the antecedents and consequences of e-SCM diffusion</td>
<td>High IT deployment capability, High operational capability, High human resource capability, High competitive performance</td>
<td>The sample size is limited to only one country</td>
</tr>
<tr>
<td>Gao and Ji (2018)</td>
<td>Investigating the influence of relationship commitment on KS in SC</td>
<td>Improving the KS among SC partners, High sense of trust</td>
<td>Limit in sample size, The lack of empirical evidence</td>
</tr>
<tr>
<td>Haque and Islam (2018)</td>
<td>Investigating the impact of SC collaboration and KS on organizational outcomes in the pharmaceutical industry</td>
<td>High product quality, High new product innovation, High customer satisfaction</td>
<td>Limit in sample size</td>
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</table>
Furthermore, Tuan (2016) has investigated the relationships between SC agility and its dynamic precursors containing organizational ambidexterity and external KS. The research has examined the moderating role of competitive intelligence for the relationship between organizational ambidexterity and SC agility. The moderating role that competitive intelligence plays in the relationship between organizational ambidexterity and SC agility was also confirmed. The findings expanded the SC literature by establishing the positive effect of organizational ambidexterity on SC agility with competitive intelligence as a moderator for this influence. However, the variables in this research may not be observable in the industrial workplace. The current research model may increase its data generalizability if it is replicated in other manufacturing industries.

Li et al. (2017) have developed and tested a conceptual framework to examine how inter-organizational KS facilitates enterprise resource planning (ERP) implementation. Data was collected from a 2014 survey on 283 Chinese companies. SEM was used to evaluate the structural model. The results have shown that organizational preparedness (in terms of availability of resources, organizational structure, and technological capabilities), positive benefits and costs perception, and external influences (in terms of environmental uncertainty, competitive pressure, and partner readiness) would ease inter-organizational KS, which in turn, would advance ERP implementation effectiveness.

Finally, Grant and Preston (2018) have developed a model to assess the social influences to mobilize SC into KS. A two-year-long empirical study examining web posts from a dedicated social supplier platform. The findings have shown that social power plays a powerful role in supporting KS even in typically competitive SCs where information and knowledge exchange is usually protected. Rewards have also been used

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<th>Paper</th>
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<tr>
<td>Rashed et al. (2010)</td>
<td>Effect of information and KS on SC performance</td>
<td>Enhancing the supplier’s operational performance</td>
<td>The model has not been evaluated in the real environment</td>
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<tr>
<td>Shih et al. (2012)</td>
<td>Investigating the role of KS in SC</td>
<td>Improving forecasting accuracy overall productivity Lowering SC costs Improving capacity realization Inventoring reduction</td>
<td>Only one firm is investigated</td>
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<tr>
<td>Singh and Power (2014)</td>
<td>Examining for the relationship between KS practices within and between trading partners is provided</td>
<td>Improving financial performance and competitive advantage firms</td>
<td>The results are not generalizable for all firms of SC</td>
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<tr>
<td>Tuan (2016)</td>
<td>Investigating the organizational ambidexterity and SC agility</td>
<td>Reducing harmful effects on the environment</td>
<td>Limited sample size and emphasis on just one aspect of the industry</td>
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<tr>
<td>Li et al. (2017)</td>
<td>Examining the SC collaboration for ERP implementation</td>
<td>Facilitating ERP implementation Low costs Enhancing ERP implementation effectiveness</td>
<td>High risk of measurement bias High inaccuracy</td>
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<tr>
<td>Grant and Preston (2018)</td>
<td>Studying using social power and influence to mobilize the SC into KS</td>
<td>Increasing motivation to share information and knowledge in the SC</td>
<td>Not measuring the size, reward, and social power</td>
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as a positive incentive to encourage an individual’s information and KS behaviors. They have shown that the economic, as well as the social environment, plays an important role in the level of engagement. While there are many effects to KS across social media networks, this research has focused on social power and social influence as antecedents. Moreover, the study has not tested the extent or strength of social influence on SC members, or the degree and strength of reward power on supplier behavior compared to that from social influence alone.

Table VI provides an overview of the most important advantages and disadvantages of the KS operational benefits mechanisms in SC. According to the reviewed studies in this section, the following benefits have been seen:

- reducing lead-time from the moment of ordering to delivery of the product;
- reducing travel cost;
- reducing SC costs and increasing income;
- reducing inventory level;
- improving production/distribution scheduling; and
- reducing communication cost.

5.4 Summary and comparison

In this section, 25 selected articles are analyzed. The main focus of researchers in the selected papers are improving some parameters such as reduced costs, quick purchasers’ access to the product, sharing knowledge and information throughout the SC, design and product innovation, proper SCM and performance improvement. However, in most studies, the sample size was limited, which causes the generalization to not be generalized. We evaluated the factors that have an effect KS on SC to find which factor is more important in any group. Furthermore, we recognized the most important and least important factors. Table VII provides an overview of the discussed KS systems on SC and their main features. In addition, we compared the achievements of the three groups of the selected papers in Table VIII. The results from indicating that the greatest benefit of KS systems in SC is improving performance, developing relationships, sharing information and managing knowledge in the SC. Future research should do a lot of research on other benefits of KS systems in SC to make the users more aware of the benefits of this technology and implement the culture of using KS systems in SC organizations. Eventually, the results of the survey showed that the main challenge and issues of KS systems in SC is trust. Therefore, issues and challenges need to be addressed.

6. Discussion

According to the performed SLR of role KS systems in SC success until 2018, we showed the number of published articles have very high 2018. Furthermore, the highest number of articles published in famous journals. Elsevier with 24 per cent, IEEE with 23 per cent, Springer 21 per cent, and Taylor with 11 per cent of published articles have the highest published articles respectively. Moreover, we identified 21528 papers, which are reduced to 25 studies through the paper selection mechanism that articles are divided into three main categories.

Research findings engender numerous implications for KS and SC literature. During this review, we showed that KS is vital to maintain organizations in a world of flexibility and competitiveness. KS among organization members and between the organization and its
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<td><strong>Strategic benefits</strong></td>
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<td>Providing a model for the reviews relational risk as a mediating construct</td>
<td>Enhancing the inter-organizational KS</td>
<td>The findings reflect the setting of Taiwan's SC only</td>
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<td></td>
<td>Ajmal and Kristianto (2012)</td>
<td>Examining the KS in SC</td>
<td>Providing the competitive advantage of green SC</td>
<td>The focus of the study is limited to one area</td>
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<td>Liu et al. (2015)</td>
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<td>Minimizing KS uncertainty</td>
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<td>Wang and Hu (2017)</td>
<td>Investigating the effects of collaborative innovation activities and capability on innovation performance</td>
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<td>Chuaynugul (2017)</td>
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<td>Huang et al. (2010)</td>
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<td></td>
<td>Cervellon and Wernerfelt (2012)</td>
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<td>High speed service</td>
<td>The sample may not represent all global SC behaviors</td>
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<td></td>
<td>Cheng and Fu (2013)</td>
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<td>Limit in sample size</td>
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Table VIII. A side-by-side comparison of the important criteria for KS systems on SC success

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<th>Classification</th>
<th>Article</th>
<th>Culture</th>
<th>Creativity</th>
<th>Rewards</th>
<th>KM</th>
<th>Organizational climate</th>
<th>Development of close relationship</th>
<th>Learning</th>
<th>Knowledge exchange</th>
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<th>Performance</th>
<th>Trust</th>
<th>Communication quality</th>
<th>Quick access</th>
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</table>
customers, suppliers, and alliance partners, greatly facilitate the process of enhancing the quality of customer service, decreasing production cycles, increasing the cooperation between many department units, and combining the relationships with alliance partners, which thus enhances the organization’s competitive benefit.

However, combining KS with innovative activities in SC can enhance the competitive advantage of organizations. To achieve this goal, business partners in SC need inter-organizational trust and collaboration to support KS intention. Based on the study conducted in this paper, we find that KS has many benefits to the success and performance of the SC, but there are some limitations. For example, corporate and industrial culture, work routines, and a high regulatory environment can have a limiting effect on the generation of voluntary engagement in KS among organizations and their SCM. In addition, many people do not share their knowledge because of the fear of losing their jobs or traditional thinking. Also, Short-term SC relationship, traditional ways of doing business has appeared “moderately challenging” factors that hinder the application of knowledge communication within an SC. The short-term relationship encourages an adverse relationship that prevents trust and collaboration. The literature review suggests that the main challenges are the lack of a KMS. Within KM systems, there is a lack of knowledge communication. Moreover, this requires developing awareness to communicate knowledge (Saini et al., 2019).

We found also that KS culture facilitates learning and KS efforts; this is crucial for an enterprise to remain innovative in its numerous production processes and managing technologies. Also, a critical component facilitating KS across the SC belongs to the trust reposed by the partners in one another. Based on Yang (2016) view, organizations would attain higher efficiency if collaborative communications prevail in an SC. Also, in global competition scenarios, rapidly changing customer demand may warrant special consideration by partners in the SC. This characteristic is exacerbated for global SC where the partners have changing the backgrounds and exposures. The development of a generic KS and management model for supporting an enterprise level super-hybrid environment needs meaningfully higher levels of innovation and advanced technology (Shih et al., 2012).

The results also showed that organizational ambidexterity as a predictor of SC agility differs from antecedents in prior SC research. Indeed, with exploratory orientation, the organization explores new knowledge, new technologies, and especially new human resources who engage in revolutionary change. Furthermore, an organization can benefit from ambidexterity not only within the organization itself but also in an SC context (Tushman and O’Reilly, 1996). We found that social power as a key driver to KS within an SC. The results of the studies showed that social power drives a dominant agent through strategies which highlight performance achievements. So, rewards have been used as a positive incentive to encourage an individual’s information and KS behaviors. The social impact generated by group norms and behavior’s, and social power through rewards, can be observed to play a role in supporting SC members in the KS process. The overall effect of social power can enhance the competitive environment, improving “customer focus” throughout the network and inadvertently and enhancing the sustainability of the SC (Grant and Preston, 2018).

To meet dynamic market demands, the firms must collaborate with partners in SC to innovate new products rapidly. Collaboration between trading partners can decrease the cost and time for effective transfer of knowledge between firms (Grant, 2002). Such value could reside in innovative KS practices providing abilities that are difficult to imitate (Nonaka et al., 2000). So, integration through collaboration between trading partners to ease innovative. Moreover, SC collaborative innovation activities increase innovation performance. As participating in collaborative innovation activities offers a number of
advantages (Slowinski et al., 2015), both customers and suppliers in an SC network can already view each and already have some knowledge of each other’s innovation abilities. This collaborative relationship can facilitate negotiations over intellectual property rights, KS, and cost recovery in common projects (Wang and Hu, 2017). Further, the importance of approaching knowledge integration from a complete view is also supported by the interdependence between internal-, customer- and supplier-focused knowledge (Singh and Power, 2014).

As a general result of KS in the SC, it improves performance, reduces costs, provides quick access to the product, and so it can be said that lack of KS is the main reason for the poor performance of SCM. Therefore, the importance of understanding drivers to KS across organizations and increasingly across supply networks is more important. Managers can only develop KM strategies if they understand the precursors of KS. The commitment relationship of SC partners has a positive effect on KS and can influence the KS behaviors of SC through reciprocity responsibility. Enterprises should maintain a sense of reciprocity responsibility among SC partners. Finally, knowledge represents a significant source of innovative potential with high strategic value.

7. Open issues
This section offers some key issues that have not been thoroughly studied until now as research directions in the development of KS systems in SC success. According to the research carried out in this study, it was observed that there is no independent method to examine all KS issues in the SC. For example, performance improvement and the development of close relationships, known as the most important effect of KS, have not been addressed in many studies. Designing a strong system to improve performance and facilitate relationships in SC is a challenge, so future studies should address barriers in SC. Also, outsourcing can provide many opportunities for enhancing a firm’s performance (Carr and Pearson, 1999).

Also, many studies did not study the specific content and form of the knowledge shared between the supplier partners. So, future research should study the implications of diverse dimensions and content of knowledge for collaborative performance. Assessing the interactions among multiple dimensions of the KS may also offer visions into the process of knowledge transfer between supplier partners. Furthermore, evaluating the influence of suppliers’ collaborative abilities on KS and collective learning is very motivating. Further investigations can show whether the new relationships regarding cultural elements and KS between project teams are usable for a broader variety of companies.

The real operational benefits of collaborative innovation are derived when efforts are made to synchronize abilities and strengths with partners for the purposes of collaborative innovation projects. Further, achieving better innovation performance through collaboration is depending on how abilities affect collaborative innovation actions. So, managers must last to focus on guaranteeing that innovation capability at a specific level is achieved, as it establishes an important step toward enhancing firm innovation performance.

Through building the KS model of enterprises in the SC, the effective KS can promote SC enterprise income. On the other hand, a valuation can be made of the alternative strategies and action plans that can be followed by the buyer to lower overall transaction costs. It also facilitates the dynamic mechanism and decision-making conditions of the chain companies. Promoting KS remains a key challenge to managers, especially across supply partners. In an SC context, group influences, as well as powerful reward incentives appear to generate KS behavior. Following on from this, the use of social media networks can motivate SC members to KS.
Organizations climate and culture, and a high regulatory environment can have a limiting effect on KS in SC. Therefore, business partners in SC need inter-organizational trust and collaboration to support KS intention. Also, the importance of understanding drivers to KS across organizations and increasingly across supply networks cannot be understated. Managers can only improve KM strategies if they understand the precursors of KS. However, promoting KS remains a key challenge to managers, especially across supply partners. So, the exhibition of the KS systems within the SC context may help practitioners and managers interested in using KS initiatives to duplicate the methodologies for enhancing the possibilities of a successful KS adoption.

While there are many effects to KS across social media networks, research in this field has not evaluated all factors affecting the KS in the SC. Therefore, comprehensive research in this area is necessary to identify all effective factors so that researchers can evaluate them. Directors should pay attention to both collaborative innovation activities and KS to improve a firm’s innovation performance in the future. Managers should understand that a firm’s best interests lie in exploiting proprietary technological knowledge without attracting imitators. This purpose may be more easily achieved in an SC relationship.

In addition, organizations should collaborate with trading partners at a full scale for inter-organizational knowledge sharing. Also, risk assessment is a very appealing line for future research (Bagal et al., 2018). Finally, the usage of fuzzy and AHP can be investigated in this domain (Ghadimi et al., 2013; Hosseini Firouz and Ghadimi, 2016; Razmjooy et al., 2017).

8. Conclusion and limitations
This paper presented a systematic and comprehensive study about KS systems in SC success until 2018 from the Google Scholar Emerald, Science Direct, and ABI/Inform Global ProQuest database and was discussed. First, a systematic selection approach has been adopted for efficient searches and a complete collective process. We determined the number of published articles have very high 2018. Furthermore, the highest number of articles published in famous journals (Elsevier 24 per cent). Furthermore, according to the studies, we categorized KS mechanisms in SC into three groups (1) Strategic benefits, (2) Managerial benefits, (3) Operational benefits. We described each of these groups separately and highlighted the advantages and disadvantages of each of them.

The important issues that studied in these years were the SCM, innovation, performance improvement, knowledge and information exchange, communications facilitation and cost reduction. The results showed that the KS in SC helps to increase the success of the organizations, improve employee performance, increase of competitive advantage, enhance of innovation, and improve relationships between supplier and consumer. However, there were weaknesses, such as staff resistance to share knowledge in the SC because of the fear of job loss. Future studies should discuss the barriers to KS in the supply chain.

There are some limitations to this study. This study limited the search to Google Scholar Emerald, Science Direct, and ABI/Inform Global ProQuest. There might be other academic journals which may be able to offer a more complete picture of the articles related. In addition, non-English publications were omitted from this study. It is possible that the research about the application of KS in SC can also be published in other languages. Finally, more studies need to be carried out using other methodologies such as interviews.
References


## Appendix 1. The abbreviation table

<table>
<thead>
<tr>
<th>State</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enterprise resource planning</td>
<td>ERP</td>
</tr>
<tr>
<td>Electronic supply chain management</td>
<td>E-SCM</td>
</tr>
<tr>
<td>Information technology</td>
<td>IT</td>
</tr>
<tr>
<td>Information systems</td>
<td>IS</td>
</tr>
<tr>
<td>Knowledge sharing</td>
<td>KS</td>
</tr>
<tr>
<td>Knowledge management</td>
<td>KM</td>
</tr>
<tr>
<td>Supply chain</td>
<td>SC</td>
</tr>
<tr>
<td>Systematic literature review</td>
<td>SLR</td>
</tr>
<tr>
<td>Supply chain management</td>
<td>SCM</td>
</tr>
<tr>
<td>Structural equation modeling</td>
<td>SEM</td>
</tr>
<tr>
<td>Linear structural relations</td>
<td>LISREL</td>
</tr>
</tbody>
</table>

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Design and fabrication of a safety frame for workers carrying out head lifting at construction sites

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Sanjay Mohan
Department of Mechanical Engineering, Shri Mata Vaishno Devi University, Katra, India

Abstract
Purpose – The purpose of this paper is to identify the musculoskeletal problems faced by the workers carrying out head lifting at the construction sites and to present a solution for the identified problems.

Design/methodology/approach – The methodology of the paper is framed in two phases. First, the identification of the problems faced by workers through interviews/questionnaire and second, designing and fabricating a mechanical system to safe guard workers against musculoskeletal disorders.

Findings – Based upon the interviews and questionnaires, it was ascertained that majority of the workers were subjected to neck pain and low back pain. This was mainly attributed to the lifting of heavy loads on head, sudden and jerky movements and bad postures.

Research limitations/implications – The developed frame has been appreciated by the Physiotherapists also; however, it still has certain limitations which can be taken as a future scope for the further modification of the frame. The limitations are as follows: the weight of the frame is a limitation, as the worker has to bear this load in addition to the load which is to be lifted. However, this can be dealt with by replacing the material of the frame with lightweight materials such as aluminium alloys, carbon fibres, etc. The continuous wearing of the frame may result in discomfort, as the worker cannot freely roam around. Sweating and etching due to wearing of belt. Worker cannot place the load him/herself on the frame. Stability issues in lifting liquids overhead.

Practical implications – Findings revealed the bleak possibility of replacing head loading. However, there is an urgent need of developing a cost-effective system which could help workers while carrying out head lifting of loads.

Originality/value – This work presents an ergonomically designed mechanical frame which will help workers in carrying out head loading without effecting their skull, spine, etc. The system was tested on workers and the results were alarming and the working capacity of the workers was observed to increase with the fabricated frame.

Keywords Construction innovation, Safety issues, Musculoskeletal disorders, Head loading, Ergonomics

Paper type Research paper

1. Introduction
Transportation of loads of different capacities has been a part and parcel of our daily routine, may it be in industry, household, construction sites, etc. Most importantly, the ways and means of transportation has a profound impact on the development of any society. Bullock carts were, and still being used for transportation of various goods, and long distances are covered by trains, trucks etc. Despite various modern ways of transportation,
lifting loads on head (head loading) still is a common practice in many parts of the world e.g. transportation of drinking water, luggage, construction material such as baskets of bricks, concrete mixture, etc.

In India, the financial activities involved in the construction industry are the second largest after that of agriculture. In addition, safe environment is still lacking at the construction sites/warehouses etc. where majority of the labours work under risky and hazardous conditions (Hamid et al., 2003). Load lifting carried out at docks in India is around 100 kg per lift, which is quite harmful for a labour performing manual lifting tasks (Saha, 1975). Furthermore, in the non-organised sector, loads as heavy as 115 Kg to 135 Kg are manually lifted by an individual worker (Sieghart, 1983). In India, and in other developing nations, head loading such as carrying bricks and concrete mixture at the construction sites is the most widely recognised practice carried out by the labourers (Maiti, 2008). Carrying load on head may lead to torment muscles, injuries in skull/brain/neck, and other spinal issues. Construction sites are an abundant source of musculoskeletal disorders, and complaints related to long-term work duration have also been associated with construction industry (Meo et al., 2013).

Work-related musculoskeletal disorders (WMSDs) and wounds are amongst the most frequently reported causes which accounts to nearly 33 per cent of all harmful and ailment cases (Bernard and Putz-Anderson, 1997; Abas et al., 2018). The maximum occurrence of musculoskeletal disorders (MSDs) has been observed in construction workers, truck drivers, cashiers, carpenters, etc. A wide range of swelling and degenerative disorders have resulted in torment muscles, functional damage and disability. Such types of disorders also influence neck, shoulders, elbows, forearms, wrists and hands (Leigh et al., 2004; Buckle and Devereux, 2002). The rising trend in WMSDs in today’s world has resulted in increased work-related disabilities (Rempel et al., 1992). It has been reported by researchers that the risks associated with a construction industry are approximately 8 times more than any other manufacturing industry (Jaiswal and Veerkumar, 2016). As reported by WHO (Unicef, 1999), Musculoskeletal disorders (MSD) are one of the largest contributors amongst different work-related illnesses. It has been recorded that work-related medical issues have caused a monetary loss of 4-6 per cent of Gross Domestic Product (GDP) for most of the nations including India (WHO, 2014). Investigation of different motions of human body leading to musculoskeletal disorders has been carried out by researchers. The study revealed various facts related to body motions which causes various disorders, and same if corrected will result in a better health condition of workers (Valero et al., 2016). The prevention of WMSDs has sought great attention from the researchers and ergonomists. The Ergonomists have designed various man-machine systems for different types of working environments, so as to ensure the safety of man without affecting the productivity. The hazards related to WMSDs in a workplace can be minimised by applying various ergonomic standards (Berberoğlu and Tokuç, 2013). Ergonomically designed tools and equipment’s have been used to reduce MSDs. The cost of such tooling in different industries or construction sites can be compensated for time loss resulting due to MSDs such as neck and back pain amongst workers (Albers and Estill, 2007). Apart from MSDs, the inclusion of ergonomics in the design of the existing tools and equipment’s can also prevent several injuries (Guptill and Zaza, 2010). The Ergonomic solutions for musculoskeletal disorders range from simple tool modification to elaborate material handling (lifting) devices and automation of construction procedures. Due to variation in manual lifting risks from site to site, the employers should create site-specific lifting programmes (Choi, 2008). The inclusion of the material handling equipment as a replacement for manual material handling seems to be costly but proves to be productive in long runs (Choi et al., 2007; Choi, 2008).
In the present work, the problems faced by workers at construction sites were established through a questionnaire and confirmed from the past literature. These live problems were taken as the basis for the design and fabrication of a safety frame to provide safety and comfort to the worker while performing manual lifting (head loading) at construction sites.

2. Materials and methods

The methodology of the proposed work has been categorised in three phases i.e. Survey, Design and Fabrication.

2.1 Survey

A survey has been carried out at different construction sites to examine the condition of workers involve in head loading (Plate 1). This investigation is supported with the interviews and the questionnaire.

2.1.1 Questionnaire. A questionnaire consisting of 31 questions is prepared by taking into consideration all parameters related to the health problems at construction sites (Silverstein et al., 2002; Merlino et al., 2003). The data pertaining to the health problems, duration, etc. is collected through this questionnaire (Table I).

2.1.2 Sampling technique. Based upon the nature of the work, a non-probability sampling technique, i.e. homogeneous purposive sampling has been chosen to collect the data, as the workers lifting load on their head are restricted in number. The purpose of collecting the data is to understand the actual problems faced by these workers while performing head loading.

2.1.3 Sample size. There were 120 workers available at five construction sites, out of which 50 were available and ready to give the responses. The data collection has been carried out using survey method via "schedule of enquiry" as most of the workers were not able to read or understand the questionnaire. The authors have translated the statements to get the responses from the workers.

2.1.4 Hypothesis. The hypothesis of the questionnaire is that the workers associated with head loading at construction sites face several health issues primarily musculoskeletal disorders, torment muscles, etc.

This hypothesis has been framed based upon the available literature. In the recent past, a lot of research has been carried out on the workers performing head loading. The literature enlightens us with the health issues faced by the workers involved in head loading especially at construction sites (Chakraborty et al., 2018; Lop et al., 2017; Wang et al., 2017). These very facts led the authors to frame a hypothesis that the workers carrying out head loading are subjected to various health issues which not only deteriorate their health, but also have negative impact on their jobs. The questions were framed after referring literature and having brain storming sessions with the experts of the fields, most prominently Physiotherapists.

Plate 1.
Workers lifting load on head
<table>
<thead>
<tr>
<th>Q. no.</th>
<th>Questions</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Are you a regular labour?</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>How many years have you been carrying out your present work?</td>
<td>13 years (avg.)</td>
</tr>
<tr>
<td>3</td>
<td>How many days per week do you work normally?</td>
<td>07 days/week (avg.)</td>
</tr>
<tr>
<td>4</td>
<td>How many hours per day do you work normally?</td>
<td>08 h (avg.)</td>
</tr>
<tr>
<td>5</td>
<td>Do you carry out the same work almost the whole day?</td>
<td>100%</td>
</tr>
<tr>
<td>6</td>
<td>Does your work involve repetitive tasks?</td>
<td>100%</td>
</tr>
<tr>
<td>7</td>
<td>Do you in your work often have to:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lift heavy loads more than 15 kg</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Push/pull heavy loads more than 15 kg</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Carry heavy loads more than 15 kg</td>
<td>100%</td>
</tr>
<tr>
<td>8</td>
<td>Do you in your work often have to:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lift with the load above your shoulder level</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Lift with a load which is difficult to grab/hold</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Lift in an uncomfortable position</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Lift with bended lower back</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Hold your neck for a longer period of time</td>
<td>100%</td>
</tr>
<tr>
<td>9</td>
<td>How many breaks do you have during a normal working day?</td>
<td>01 (1 h)</td>
</tr>
<tr>
<td>10</td>
<td>Are your normal breaks sufficient?</td>
<td>34% 66%</td>
</tr>
<tr>
<td>11</td>
<td>Is your work often hampered by uneven working place?</td>
<td>100%</td>
</tr>
<tr>
<td>12</td>
<td>How is your health status in general</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Fairly good</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>Not too bad</td>
<td>28%</td>
</tr>
<tr>
<td></td>
<td>Poor</td>
<td>10%</td>
</tr>
<tr>
<td>13</td>
<td>How tired are you physically at the end of a working day?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not tired</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>A bit tired</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>Tired</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>Very tired</td>
<td>66%</td>
</tr>
<tr>
<td>14</td>
<td>How tired are you mentally at the end of a working day?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not tired</td>
<td>48%</td>
</tr>
<tr>
<td></td>
<td>A bit tired</td>
<td>34%</td>
</tr>
<tr>
<td></td>
<td>Tired</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td>Very tired</td>
<td>4%</td>
</tr>
<tr>
<td>15</td>
<td>How frequent you go to the doctor?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Once a week</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Two days in a month</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>Once in a month</td>
<td>36%</td>
</tr>
<tr>
<td></td>
<td>Once in two months</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>Note: rest 28% of labour is not suitable for this question</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Have you consulted the doctor in the past six months?</td>
<td>78% 22%</td>
</tr>
<tr>
<td>17</td>
<td>Do you have trouble now (pain, discomfort) from your-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Neck</td>
<td>56% 44%</td>
</tr>
<tr>
<td></td>
<td>Shoulders</td>
<td>44% 56%</td>
</tr>
<tr>
<td></td>
<td>Hands</td>
<td>18% 82%</td>
</tr>
<tr>
<td></td>
<td>Lower back</td>
<td>70% 30%</td>
</tr>
<tr>
<td></td>
<td>Hip</td>
<td>48% 52%</td>
</tr>
<tr>
<td></td>
<td>Legs</td>
<td>52% 48%</td>
</tr>
</tbody>
</table>

Table I. Average value (%) of the responses (continued)
<table>
<thead>
<tr>
<th>Q. no.</th>
<th>Questions</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>Have you had pain during the last six months in your Neck</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>Seldom</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>Regular</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>Severe</td>
<td>48%</td>
</tr>
<tr>
<td></td>
<td>Never</td>
<td>0%</td>
</tr>
<tr>
<td>19</td>
<td>Have you had pain during the last six months in your Shoulders</td>
<td>56%</td>
</tr>
<tr>
<td></td>
<td>Seldom</td>
<td>56%</td>
</tr>
<tr>
<td></td>
<td>Regular</td>
<td>34%</td>
</tr>
<tr>
<td></td>
<td>Severe</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>Never</td>
<td>0%</td>
</tr>
<tr>
<td>20</td>
<td>Have you had pain during the last six months in your Hands</td>
<td>66%</td>
</tr>
<tr>
<td></td>
<td>Seldom</td>
<td>66%</td>
</tr>
<tr>
<td></td>
<td>Regular</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>Severe</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>Never</td>
<td>0%</td>
</tr>
<tr>
<td>21</td>
<td>Have you had pain during the last six months in your Lower Back</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>Seldom</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>Regular</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>Severe</td>
<td>62%</td>
</tr>
<tr>
<td></td>
<td>Never</td>
<td>0%</td>
</tr>
<tr>
<td>22</td>
<td>Have you had pain during the last six months in your Hip</td>
<td>48%</td>
</tr>
<tr>
<td></td>
<td>Seldom</td>
<td>48%</td>
</tr>
<tr>
<td></td>
<td>Regular</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>Severe</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>Never</td>
<td>0%</td>
</tr>
<tr>
<td>23</td>
<td>Have you had pain during the last six months in your Legs</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>Seldom</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>Regular</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>Severe</td>
<td>36%</td>
</tr>
<tr>
<td></td>
<td>Never</td>
<td>0%</td>
</tr>
<tr>
<td>24</td>
<td>Have you ever been treated medically for an injury caused during work?</td>
<td>42%</td>
</tr>
<tr>
<td>25</td>
<td>What caused your neck/shoulder pain –</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>A sudden movement</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Lifting of heavy loads for a long period of time</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>A bad posture</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Poor load lifting/unloading technique</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>The climate changes</td>
<td>100%</td>
</tr>
<tr>
<td>26</td>
<td>Did you ever have a cervical problem?</td>
<td>56%</td>
</tr>
<tr>
<td>27</td>
<td>Is your neck/shoulder pain associated with your work?</td>
<td>56%</td>
</tr>
<tr>
<td>28</td>
<td>What caused your lower back pain –</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>A sudden movement</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Lifting of heavy loads for a long period of time</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>A bad posture</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Poor load lifting/unloading technique</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>The climate changes</td>
<td>100%</td>
</tr>
<tr>
<td>29</td>
<td>Did you ever have a spine (slipped disc) problem?</td>
<td>50%</td>
</tr>
<tr>
<td>30</td>
<td>Is your lower-back pain associated with your work?</td>
<td>50%</td>
</tr>
<tr>
<td>31</td>
<td>How many days were you on sick leave due to lower-back pain?</td>
<td>2 days (avg.)</td>
</tr>
</tbody>
</table>
2.1.4.1 Design. To shape the mechanical frame, several trials have been made based upon the anthropometric details and safety of the workers. These trials are followed by material selection and modelling of the frame using CAD software. The developed model has been analysed for stress and deflection using analysis software.

2.1.4.2 Fabrication. The finalisation of design of the frame using CAD software is followed by the real time fabrication. Various basic processes have been used to carry out the fabrication.

3. Results and discussions

3.1 Analysis of the survey responses

To find the severity in the health problems faced by workers, an average percentage value is calculated for each of the response received from the workers. The percentage value of responses along with the questions has been shown in Table I. The responses obtained from the collected data have been compared with the past responses reported by many researchers (Table II). It is observed that the present investigation is more comprehensive as it involves analysis of pain in limbs which had not been included by other researchers in their studies. Further, the analysis carried out by the authors is in line with the past literature. The analysis of the responses has revealed that there is an urgent need for safeguarding the workers against pain/discomfort in different limbs of the body. Figure 1 shows the analysis of the questions being asked to the workers. These questions have led the authors to ensure that there are health issues with the workers involved in lifting load on head. Figure 1(a) shows that majority of the workers are subjected to tiredness, and they frequently visit doctor as depicted in Figure 1(b). Further, the body parts subjected to pain or discomfort during head loading are shown in Figure 1(c). As per the questionnaire, next level is to determine the frequency of occurrence of the pain amongst the workers in each of the limbs. Figure 1(d) to Figure 1(i) shows the occurrence of pain as reported by the workers. Apart from seldom and regular criterions, majority of the workers have reported severe pain in neck and low back [Figure 1(g) and (d)]. This has also been reported by many other researchers (Bernard and Putz-Anderson, 1997; Buckle and Devereux, 2002; Alghadir and Anwer, 2015).

<table>
<thead>
<tr>
<th>Risks</th>
<th>Current data analysis (Rahaman et al., 2017)</th>
<th>Past data analysis (Reddy et al., 2016)</th>
<th>Past data analysis (Alghadir and Anwer, 2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck</td>
<td>56%</td>
<td>92%</td>
<td>Not mentioned</td>
</tr>
<tr>
<td>Shoulders</td>
<td>44</td>
<td>58</td>
<td>12</td>
</tr>
<tr>
<td>Hands/Wrists</td>
<td>18</td>
<td>36</td>
<td>11</td>
</tr>
<tr>
<td>Lower Back</td>
<td>70</td>
<td>62</td>
<td>20</td>
</tr>
<tr>
<td>Hips/Legs/Knee</td>
<td>48</td>
<td>Not mentioned</td>
<td>Not mentioned</td>
</tr>
<tr>
<td>Level of Risk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seldom/Moderate</td>
<td>43%</td>
<td>28%</td>
<td>Not mentioned</td>
</tr>
<tr>
<td>Regular</td>
<td>27</td>
<td>Not mentioned</td>
<td>Not mentioned</td>
</tr>
<tr>
<td>Severe</td>
<td>30</td>
<td>40</td>
<td>Not mentioned</td>
</tr>
<tr>
<td>No pain</td>
<td>0</td>
<td>10</td>
<td>Not mentioned</td>
</tr>
</tbody>
</table>

Table II. Comparison of risks amongst workers in construction industry.
It is pertinent to mention here that the percentage pertaining to above mentioned problems will increase as the number of observations increase. The most common causes of the health issues faced by the workers has been summarised, and are as mentioned below:

- sudden movements during working hours;
- lifting of heavy loads for a long period of time;
- bad postures;
- poor load lifting/unloading technique; and
- the working environment.

The identification of the health issues amongst the workers carrying out head loading has formed a strong basis for the fabrication of a mechanical system (Frame), which will not only safeguard them from several musculoskeletal disorders but also induce motivation amongst them. The detailed design and testing of the Frame has been discussed in the succeeding sections.

3.2 Design
The objective here is to develop an ergonomic mechanical structure to enhance safety of the workers performing head loading. With reference to the past literature (Johnston et al., 2008;
Haag, 1992; Hoe et al., 2012) and the responses sought from the workers, several discussions were held with the experts from the area of ergonomics and Physiotherapy. These discussions have helped in devising major safety features which are to be considered while designing the frame. The list of the safety features is as mentioned:

- free neck rotation;
- limited twist of waist;
- limited or no forward bending of neck;
- use of vertical postures during lifting rather than waist;
- minimum distance between centre of gravity of the worker and load;
- transfer of load from head to shoulders;
- minimal engagement of hand during lifting; and
- multiple load lifting.

3.2.1 Initial trials. Based upon the safety features as mentioned in Section 3.2, the authors underwent many trials, and finally the drawings of the frame are prepared as shown in Figure 2. The initial drawings comprise mainly of three components, i.e. upper frame, lower frame and middle frame. The safety features discussed above have been incorporated in the supporting structure as explained below:

- The upper frame will be a square frame which will hold lifting pans in a balanced way and will result in free neck rotation.
- The length of the middle frame will be adjusted in such a way so that it restrains the turning of the waist.
- There will be no bending of neck, as the developed system will result in neck free loading.
- Due to the length of the middle frame, worker has to sit or stand straight to lift the load. This will ensure the usage of vertical postures during lifting.
- To ensure uniform and balance lifting, the centre of gravity of the frame and the worker will have minimum distance between them. This is due to the rigid fixation of frame to the body of the worker.
- The frame will be fixed to the worker by belts around the shoulder and waist. This will result in supporting of the lifted load by the shoulders.

![Figure 2. Initial drawings](image-url)
The proposed frame will result in minimum engagement of hands in holding the pan due to the proper balanced lifting.

The lower frame can be used for lifting materials like bricks simultaneously along with the head lifting.

To have a realistic visualisation of the frame, the initial drawings are modelled into a frame mounted on the worker as shown in Figure 3.

3.2.2 Material selection. Material selection has been carried out based upon the availability, cost, strength and weight. The materials namely steel, aluminium, glass fibre etc. have been frequently used in fabrication processes, and based upon these factors; stainless steel has been used for fabrication in the present study (Huyett, 2000).

3.3 Modelling and analysis

To ensure the strength of the frame, a CAD model (Figure. 4) of the frame has been developed. The frame is subjected to real loading conditions (1000 N), and stress values along with deflection at different locations have been checked for safety.

3.3.1 Modelling. The parameters considered while modelling the frame have been finalised based upon the onsite observations and the past literature as shown in Table. III (Legg and Mahanty, 1985; Bloom and Woodhull-Mcneal, 1987; Stuempfe et al., 2004). The average height of the workers i.e. 165 ± 5 cm (avg.) is obtained from survey carried out at the construction sites. The percentage height of upper body and lower body is considered 45 and 55 per cent (approximately) of the average height (Grandjean and Kroemer, 1997). The size of the upper frame is decided based upon the average size of the pan used by the workers, and the average diameter of the pan is around 40 cm. To balance the pan on the upper frame (Figure 2), a frame with square cross section is modelled with each side of 31 mm. The height of the middle frame has been finalised based upon the average torso height of the workers. From the data collected at the sites, the torso height falls in the range of 51 ± 3 cm. The final height of the middle frame is taken as 78 cm so that whole back gets supported and safety features such as turning of waist, straight postures during lifting are incorporated. The positioning of belts has been made corresponding to the average neck height obtained from the workers at the sites, i.e. 30 ± 3 cm. This positioning of the belts helps in lifting without having any contact of head with the load. The belts also prevented any bending moment on the frame due to the load placed on head.
3.3.2 Analysis. Structural analysis of the frame is carried out using ANSYS 16.0 software. From the survey, it is observed that the head load carried by the workers varies between 20-40 Kg. However, to develop a strong frame, the load acting on the upper frame is taken to be 1000 Newton (100 kg approx.) as shown in Figure 5. The distribution of load is made uniform throughout the upper frame. The stress analysis has been carried out using Von Mises Failure criteria. The stress and deflection values of the frame are then compared with that of SS304, and the fabricated frame is found to be safe from strength point of view as it is within permissible limits as shown in Figure 6. The maximum deflection of the frame is around 0.070 mm which is also within safe limits (Figure 7).

3.4 Fabrication
The fabrication of the metal frame does not involve any complex processes. Very basic machining processes such as cutting, welding, grinding, etc. have been used in the fabrication of the frame. The hollow steel frame of square cross-section has been used to create the base structure as shown in Plate 2. The joints of the middle frame are welded, and the upper and lower frame are joined to the middle frame using hinges. The upper and lower frame can be folded and carried with ease as shown in Plate 2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Measurements (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of the worker</td>
<td>165 ± 6 cm</td>
</tr>
<tr>
<td>Height from shoulder to top of head</td>
<td>30 ± 3 cm</td>
</tr>
<tr>
<td>Torso height</td>
<td>51 ± 3 cm</td>
</tr>
<tr>
<td>Diameter of pan used in lifting</td>
<td>55 ± 5 cm</td>
</tr>
</tbody>
</table>

Table III. Anthropometric measurements
The support system for the back of the worker is developed using glass fibre, as it is light in weight and has good strength (Plate 3). Polyurethane (PU) foam is fixed to glass fibre and a bulge is provided as shown in Plate 3. The objective of providing a bulge is to safeguard the worker against any bend incurred at lower back during the lifting. Finally, the fibre with PU foam is covered with Rexene material (Plate 3), and is fixed with a steel sheet. This whole support system is then fixed to the middle frame (Plate 4). The belts have been provided to the frame so that worker can easily mount the frame on their back. Moreover, the belts also transfer the load lifted by the worker to the shoulder and back.

The detail of the material used for the fabrication of metal frame is listed in Table IV.
3.5 Testing

The authors have considered the responses obtained from the data as the basis for developing a mechanical system which will be a step taken towards the safety of workers against such hazards. The developed frame has been tried and tested with workers at the construction sites as shown in Plate 5. Due to past practice of head loading, the workers have shown resistance in using the frame for lifting purposes. However, they were apprised about their health problems arisen due to their current practice of lifting, and were then asked to give a trial. Thereafter, the workers wore the frame and begin lifting of load. Due to the limited number of frames, the authors have tested the frame with limited workers. However, the responses from the workers were encouraging. The liking of the frame is mainly due to free head/neck movement, less bending and multiple loading. The fact cannot be denied that wearing such frame on continuous basis will create fatigue on shoulders and back, but workers can take out the frame after carrying out some lifting. Moreover, the productivity of the worker is observed to increase with these types of frames as they not only bring worker in safe zone but also creates a motivation amongst them.

Figure 7.
Deformation in the frame

Plate 2.
(a) Isometric view of the frame; (b) side view of the frame; and (c) folded frame
4. Limitations

The developed frame has been appreciated by the Physiotherapists also; however, it still has certain limitations which can be taken as a future scope for the further modification of the frame. The limitations are as mentioned below:

- The weight of the frame is a limitation, as the worker has to bear this load in addition to the load which is to be lifted. However, this can be dealt with by replacing the material of the frame with lightweight materials such as aluminium alloys, carbon fibres, etc.

- The continuous wearing of the frame may result in discomfort, as the worker cannot freely roam around.

Plate 3. (a) Glass fibre for back support; (b) pu foam fixed on glass fibre; and (c) rexine covered back support

Plate 4. (a) Front view of frame; (b) side view of frame; and (c) back view of frame

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel (304 S30400)</td>
<td>4.5 kg</td>
</tr>
<tr>
<td>Glass fibre</td>
<td>24&quot; X 12&quot;</td>
</tr>
<tr>
<td>Polyurethane (PU) foam</td>
<td>10&quot; X 12&quot;</td>
</tr>
<tr>
<td>22 mm (72&quot; X 36&quot;)</td>
<td>21&quot; X 12&quot;</td>
</tr>
<tr>
<td>12 mm (72&quot; X 36&quot;)</td>
<td></td>
</tr>
<tr>
<td>Rexine</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Nut and bolts</td>
<td>200 gm</td>
</tr>
<tr>
<td>Aluminium sheet</td>
<td>200 gm</td>
</tr>
<tr>
<td>Plastic fibre belts</td>
<td>10 m</td>
</tr>
</tbody>
</table>

Table IV. Material details
5. Conclusions

The work presented in this paper is based upon the problems faced by the workers involved in lifting load on head. The findings of the present work have led to the development of a physical system which has been tried and tested by workers. The journey from conceptualisation of the frame to its physical existence involves the response of workers, experts of the relevant streams such as Ergonomists and Physiotherapists. The safety of man with machine has been elaborated by Ergonomists, whereas Physiotherapists have ensured the presence of MSD in workers and the ways and means to handle them. These experiences have led to the conceptualisation of the developed frame. The construction companies have been apprised about the benefits of using these frames. The companies will save a large sum of money paid as a medical insurance for the injured workers. The companies have to initially go for very small investments for developing these frames and this will not only save medical expenditures but will also increase productivity. Further, the work carried out in this study can be concluded as:

- A survey was carried out on 50 workers involved in lifting weight on their head at different construction sites.
- The survey revealed that 100 per cent workers perform heavy and prolonged load lifting.
- Out of all workers selected for study, 98 per cent have reported unhealthy environment, i.e. 60 per cent expressed fairly good environment and 38 per cent reported poor working environment.
- At the end of the day, fatigue i.e., extremely tiresome condition has been reported by majority (66 per cent) of the workers.
- The workers were subjected to pains in different parts of the body, and amongst them low back pain (70 per cent) and neck pain (56 per cent) were the most prominent.
- A mechanical frame has been designed and fabricated wherein safety of the worker carrying out head loading has been ensured.
- The safety of the frame is ensured by carrying out stress and deflection analysis of the using CAD modelling and analysis.
- The frame was fabricated and tested on workers at the construction sites.
References


Further reading

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Investigation of crack in beams using anti-resonance technique and FEA approach

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Abstract

Purpose – In the case of machines, structures and assemblies, the crack generation and propagation is becoming a great concern, especially in airplane wings, turbine blades and such other applications. This is because these parts are very large in size and the crack size is very small, i.e. in microns. Hence, there is an important need to locate the crack and to find its severity before it starts to propagate and also to detect these parameters by on-site non-destructive testing methods. This paper aims to develop and test the methodology to locate an unknown single open crack in steel cantilever beam along with its severity.

Design/methodology/approach – This study covers analytical, numerical and experimental analysis for healthy and cracked beams. Vibration-based approach and finite element analysis (FEA) approach is used for analytical and numerical study respectively. Own designed and dedicated experimental set-up is used for testing purpose along with fast fourier transform analyzer. An anti-resonance technique is used to locate and to find the severity of unknown crack. The statistical approach helps to validate the results.

Findings – The comparison of the natural frequency of healthy and cracked steel cantilever beam shows that the crack in the beam reduces its natural frequency. The accuracy of results is achieved by finding actual density and Young’s modulus of steel specimen under consideration. It is helpful to verify the health of the non-cracked beam by applying dye testing. The study of natural frequency and anti-resonance gives the location of crack and its depth also. The FEA approach proved to be an important tool for numerical analysis of cracked beam.

Research limitations/implications – The research is limited to steel material and surface cracks only.

Practical implications – Practically, this study highlights how to locate a surface crack in steel beam along with its depth, i.e. severity with great accuracy. Identification of the factors such as location and depth of a crack provide the severity of damage in airplane wings, turbine blades, bridges and many more, and thereby, it helps in safety at working vicinity.

Social implications – The identification and solutions of current research helps to predict the operational life of machine elements such as airplane wings, turbine blades, bridges and many more, and thereby, it helps in the safety of people in working vicinity of such structures.

Originality/value – The work presented, is based on original research and experimentation. This work is valued contribution in the field of methodologies applied for fault detection in structures and also determining its correctness by numerical and experimental work.

Keywords Finite element analysis, Crack, Vibration, Antiresonance, FFT analyzer, Steel beam

Paper type Research paper

The author is greatly thankful to Nath Wire Cut Pvt. Ltd., Aurangabad (Maharashtra state, India). The company has extended their great support and spends valuable time for accurate wire cutting on all beams in this research.
**Introduction**

Any machine or structure is made up of numerous small elements, and thus, the performance of the overall machine is dependent on the individual performance of such small assemblies. In many cases, these elements are standardized, while in a few cases it is custom made. During the machine design process, a design engineer must have the thorough knowledge of structural elements. These structural elements are used to decompose or split-up the complex structures into simple elements such as beams, columns and plates. When anybody says design analysis of any element then, it meant for material specifications, types of loadings, a factor of safety, dimensions, manufacturing processes, maintenance, reliability, etc. The elements such as beams, plates, shells carry different types of loadings and thus are different in dimensions, size and shapes. Similar to the performance, the failure of any small component may stop the functioning of the whole machine. Hence failure analysis of such all elements becomes the most important task. The failure analysis includes failure cause and failure effects. If we concentrate on failure cause, then the failure itself and its adverse effects can be avoided. The general failure causes are design failures, working atmosphere and operational errors, management failures, maintenance induced failures and specifications failures. Because of these reasons, some defects are generated in elements during their working, and they are the ductile and brittle fracture, excessive deflection, buckling, impact, various types of fatigue, corrosion, shock, wear and tear, etc. Each of these has generally, a common outcome, i.e. a crack or fracture at the surface. In the power generation sector, the main cause of turbomachinery parts failure is the crack initiation due to low cycle fatigue. So, there is a great need of methods for on-site monitoring and crack detection. To detect a crack or fracture in any machine elements such as beams, plates and rods, various methods were used by researchers Dimarogonas (1996), including different NDT methods. Dimarogonas, in his report, has mentioned that the vibration-based fault detection methods are gaining wide response in the power generation sector and other industrial practices. He has developed a theory for crack detection in turbine blades which was based on vibration theory. Effect of crack on vibration parameters is a major concern in these studies. Some vibration parameters are basic such as natural frequency, amplitude or mode shapes, but some parameters are derived from basic parameters such as transfer matrix Patil and Maiti (2003). Also, few researchers had done the only numerical study and thereby proposed new crack detection techniques. But other researchers had done an analytical, numerical and experimental study and validate their results. For the numerical study, it is a common practice observed that finite element analysis (FEA) approach is widely used. This is because it is less time-consuming, giving more accurate results, and easy to handle. For experimental study, it has been observed by the author, that there is a variation in beam material, beam dimensions, support conditions, also there is a change in crack location, its width and depth in the beam. Based on all these variations and combinations, numbers of papers are published by the research community.

**Literature survey**

Dimarogonas (1996) has collectively shown the array of work done in this area up to 1996. In this paper, he has explained how crack detection by vibration became important between 1960 and 1970. Dimarogonas worked on the relation between the crack in structure and its vibration response. He also focused that during vibration amplitude, crack is either open or close. The presence of a local defect such as crack affects the dynamic response of any structural member. The crack introduces new harmonics in the vibration spectrum of the structural member. Dimarogonas mentioned that there are extensive laboratory and field
experiments done to develop a methodology for crack detection based on harmonics and sub-harmonics theory. Dimarogonas has mentioned the names of many researchers who relate the local flexibility to the crack stress intensity factor (SIF). Fine mesh finite element techniques are also developed by many people in 1983 and are compared with experimental results. The presence of the crack reduces its stiffness and consequently the natural frequency of a member. Dimarogonas in his reports to General Electric Company, establish the relation between crack depth and reduction in natural frequency. For small crack depths, excitation frequency response shows peaks at first three natural frequencies. If the crack depth goes on increasing, then other peaks are also observed at subsequent natural vibrations. The turbine blades with single crack are studied from many decades. These blades are modeled as the cantilever beam with local flexibility at the crack it is important to monitor cracks with small depths at an initial stage so that to assure the safety before any major loss. Around 500 papers were published on crack detection from 1971 to 1992. But still, consistent cracked bar vibration theory is not yet developed and still is a scope of study especially about closing cracks in rotating shafts.

In the area of multiple crack detection, Lee (2009) has also contributed well with new techniques. In his work, the cracks are modeled as mass-less rotational springs. The forward problem is solved with the help of the finite element method, while, the inverse problem is solved in an iterative way using Newton–Raphson method and singular value decomposition method. The beam used for analysis was C30 steel beam with length 0.8 m and a square cross section of 0.2 × 0.2 m. Two cracks had been generated on beam with crack depths ratio of 20 and 30 per cent, while crack location ratios were 31.82 and 68.12 per cent. The cracks were created by wire erosion method with the width of 0.13 mm. Lee has suggested an alternative way to calculate Young's modulus of the steel beam. This method is based on natural frequencies obtained from experimentation and is found fairly accurate. The same method is used in current research work also.

Lee had put forth a very important investigation about torsional stiffness model. He had proved that torsion stiffness k = k1 and k = k2 taken by Ostachowicz - Krawczuk and Dimarogonas - Paipetis are not much sophisticated. Hence, he performed several trials and found scaling factors as k = 0.83 k1 and k = 0.65 k2. These factors gave better results. In case of an inverse problem, Lee assumed that vibration amplitude measurements are available. He applied the Newton–Raphson method taking crack parameters as α1, α2, ..., αk, β1, β2, ..., βk for “k" number of cracks. Here, “α” is crack depth ratio i.e. a/h and “β” is x/L, i.e. crack location. Then he performed iterations on Jacobian matrices to find the above parameters. He assumed initial gaussses and then finally obtained correct values. The errors found in crack location are within 0.0048 and for crack size; they are within 13 per cent of actual size.

For the finite element model, Lee has used Euler–Bernoulli beam theory. For simulation purpose, Lee has made 2d ANSYS model. In the case of the inverse problem, initially crack parameters, i.e. crack depth ratio and crack location ratio have been assumed. Then iterative methods are used to find accurate results, several attempts are required to reduce residuals after each iteration. During this inverse problem, statistical terms are used such as range, mean and standard deviation for crack parameters and input random noise. In an analysis, the number of equations was more than the number of crack parameters hence they are solved by least square sense.

For multiple crack detection, Patil and Maiti (2003) also used rotational spring for modeling the cracks, and they have also used Euler–Bernoulli beam theory. They have presented the transverse vibration of the beam by combining rotational springs with a transfer matrix method. Rotational spring is used to divide the beam into small segments.
The huge mathematical formulation is done on natural frequency and damage parameter of each segment. The method studied is approximate and about the accuracy of the method, it is stated that maximum difference in the prediction location is less than 10 per cent and the difference in the size is less than 15 per cent. The study also has one limitation. Maximum number of cracks that can be detected is less than or equal to the number of segments into which the beam is virtually divided. Also, the method adopted, cannot be used where rotational inertia, shear deformation, and damping effects are significant.

Similar work of crack detection and finding its size is also done by Ruotolo and Surace (2005) multi-cracked beams. They had used FEA approach for the analytical study of structures. In case of an inverse problem, they had used a genetic-algorithm optimization technique. Simulation and experimental study is carried out on steel cantilever beams with varying crack location and crack sizes. The method under consideration of this research is structural damage identification technique. The steel used here is C30 with a cross-section of 0.02 m x 0.02 m and length of 0.8 m. They have divided the beam into 11 segments of equal lengths. The cracks on the beams are generated by wire erosion with 0.10 mm diameter and found to be 0.13 mm wide. In this study, the least squares technique is used for mode shapes.

A numerical technique for crack detection in a beam is suggested by Chinchalkar (2001). The depth of crack is varying and only the first three natural frequencies are taken for study. Here, also crack is modeled as rotational spring. For the numerical study, the FEA approach has been used. A difference of this study is that beam of varying cross-section has been used. The numerical method they used is general enough to handle the variations of beam cross-section. The wedge-shaped beams are associated with truncation factor “a”. For different values of “a”, the first three natural frequencies with different boundary conditions are found out by two approaches one is FEM approach and the other is Frobenius, i.e. semi-analytical method.

Steel is a material referred by many researchers. But there is aluminum also on which study is done. Owolabi et al. (2003) used two sets of aluminum beams. Each set contains seven beams. The boundary condition for one set is fixed-fixed while for others it is simply supported. Each beam is of square cross-section of 25.4 x 25.4 mm and the length is 650 mm. modulus of elasticity used is 70 GPA, density is 2.696 gm/cm$^3$ and Poisson’s ratio is 0.35. They have done experimental analysis only and hence very little mathematical formulation is needed. Seven beams of one set carry seven cracks one crack on each beam. The depth of cracks for seven cracks is varying from 0.1 to 0.7d, where d is the total depth of the beam. Crack location is evenly spaced along the beam length for seven beams. Crack width is not so finely produced, and it is generated by saw cutting with the width around 0.4 mm. during testing with fast fourier transform (FFT) analyzer, an impact is given at a location where a crack is not located so as to avoid the nodal point of mode shape because obviously there would be no response there. For data analysis, STAR (structural testing, analysis and reporting) software package is used and results obtained are curve-fitted with this software.

Dilena and Morassi (2004) have used the new technique for cracked detection in single cracked beams. They found that if we use only natural frequency data then there is a problem of non-uniqueness in damage location. Hence, along with natural frequency data, they have used the antiresonant frequency of the structure. Their study is based on measurements of damage-induced shifts in natural frequencies as well as antiresonant frequencies. For verifying the theoretical results, they have performed experiments on cracked steel beams under free-free boundary conditions.

In many studies of damage detection, the change in natural frequency was widely used as a diagnostic tool, Boltezar et al. (1998). Some of the researchers have assumed that the
crack stiffness is not dependent on vibration frequency. The existence of crack introduces irregularity in vibration mode shapes of the structure. The same technique has been used by Wang and Qiao (2008). Jialai et al. determine location and size of crack by the peak value of irregularity, appearing on the profile. The method is suitable for single and multiple cracks also. To validate numerical results, experimentation is done on an epoxy laminated composite beam. The cracks were generated by the saw cut. Though the method is not demanding the knowledge of healthy structure it requires multiple sensors to obtain different mode shapes of the structure. For this, Jialai et al. have used scanning laser vibrometer (SLV).

The importance of antiresonance is more elaborated by Wahl et al. (1999). He stated that, for any arbitrary boundary conditions of the structure, the resonance frequency can be obtained for ideal boundary conditions, which is difficult to achieve in laboratory testing.

The concept of the driving point is used by Bamnios et al. (2002). The same is used in the current paper also. The effect of crack on the mechanical impedance of the beam is studied. The sudden jump in the antiresonance frequency plot is an indication of the crack location and the magnitude of jump indicates the size of the crack. Similar to Bamnios, the analysis is done and similar types of curves are obtained by Wang et al. (2007).

Masango et al. (2018) in their report focused on instant structural health monitoring system (SHM). This is also in situ technique. In this work, researchers have used Poly-Vinyli-Dene Fluoride (PVDF) sensors for locating the defects in flexible composite structures. These defects are artificially made in the form of drilled hole of 3 mm diameter. Vacuum infusion process is used for fabricating composite plate. The “cantilever” boundary condition is used during experimentation. The Fluke – View Scopemeter is used to record the data obtained from PVDF sensors.

Authors have tested sixteen samples with same dimensions of 280 mm length, 69 mm width and 2 mm thickness. The resin and carbon fibre was used to manufacture composite and is widely used in unmanned aerial vehicle (UAV). The three-point bending tests and deflection test were performed. From these tests, young’s modulus was determined. Also, the capabilities of PVDF sensor is tested for continuously monitoring the structural health.

This technique works on very simple principle that when defect exists on structure then more deflection occurs and more deflection results in high voltage output from sensors. The authors have used different masses to record corresponding deflections. These masses start from 50 g up to 450 g in the interval steps of 50 g. These masses are hanged at the free end of the beam. The defects are made in the form of 3 mm drilled hole and their locations are 50, 100, 150 and 200 mm from fixed end. Output voltage from PVDF sensors are recorded for varying defect location and masses. Then it is compared with healthy, i.e. defect-free sample. Authors have pointed some good observations. The deflection of damaged beam is more as compared with damage-free beam. The reason is the reduction in stiffness of beam because of defect. One of the important results that authors mentioned is about defect location. If defect location is very close to fixed end of cantilever beam, then the beam deflection is more. We know that, higher stress concentration is at fixed end for cantilever boundary condition. So, when defect is very close to high stress concentration region, the deflection is more.

The important finding from this work is the capable tool for monitoring the structural health. PVDF sensor is a capable tool for detecting the presence of the defect through the output voltage.

Eroglu and Tufekci (2016) present a new formulation for finite element analysis. They have used straight beams with edge crack. They also consider effects of shear deformation and rotator inertia in their study. This FEM formulation is obtained by the exact solution of the beam equation. They have considered only in-plane motion of the beam. The shear
deformation, axial deformation and rotator inertia are also considered during study. They have modelled the crack as a rotational and two translational springs. Inverse problem is solved by well-known genetic algorithm (GA) technique.

The experimental study is carried out on steel St32 beam with rectangular cross-section with 20 mm height and 8 mm width. The length of the beam is 800 mm and the boundary condition is cantilever. Two specimens are used during experimentation, one is healthy and other is damaged. The crack is located at a distance of 500 mm from fixed end. The width of crack is 0.15 to 0.18 mm, while its depth is 3 mm. Wire erosion is used to create crack with wire diameter of 0.1 mm. In this experimentation also, the excitation to the beam is applied at eight equidistant points, while response (i.e. output) is measured only at a single point which is located at a distance of 300 mm from the fixed end. The range for frequency measurement is 0 to 1,600 Hz. The presented FEM model is useful for accurate modelling and better results in damage parameter identification.

Altunisik et al. (2017) have also used transfer matrix method (TMM) for analytical solution to solve the problem of crack detection. For numerical study, they have used finite element method for numerical analysis and the results are verified by experimental study. Authors have used steel beam with Young’s modulus of $206 \times 10^9 \text{N/m}^2$, density of 7850 kg/m$^3$ and Poisson’s ratio of 0.3. Beam is mounted with cantilever condition and having hollow circular cross-section. The length of beam is 1,000 mm and outer diameter is 102 mm with wall-thickness of 4 mm. Three cracks are generated on a single beam at a distance of 250 mm, 550 mm and 850 mm. A typical transverse crack is used for study purpose which is common in several applications. The combination of two depths of crack are used which are 15 mm and 50 mm. For numerical study, authors have created 3D finite element model using solid elements in ANSYS Workbench. Here also, the first three natural frequencies are considered. Six accelerometers are mounted at a time on beam. Among several available methods of modal parameter identification methods, authors have used the enhanced frequency domain decomposition (EFDD) method in frequency domain, while stochastic subspace identification (SSI) method in time domain. The mathematical background of these methods is quite similar only the difference is in implementation aspects.

Authors pointed out the extent of effect on dynamic characteristics of beam. The modal performance is greatly affected by crack size as compared to number of cracks. The results obtained from experimentation are different than numerical or analytical because the boundary condition if quite difficult to achieve in laboratory experiments. This difference is greater than 10 per cent. But still, the results obtained from analytical, numerical and experimental study are in good agreement with each other. Authors have used two derived quantities as damage indicators; these are modal assurance criterion (MAC) and the coordinated modal assurance criterion (COMAC). Both these quantities are derived from the observation sets of calculated and measured mode shapes. MAC values provide the information about the overall change in stiffness due to damage, but are not helpful in prediction of crack location. On the other hand, change in COMAC gives the stiffness reduction at cracked location. In the same paper, authors have mentioned the importance of model updating process so as to achieve correct boundary conditions in numerical and experimental study.

Elshamy et al. (2018) have also used cantilever as boundary conditions for damage analysis of beams. Similar to previous researchers, the study has been done. The difference is the consideration of probe mass during data acquisition. Two approaches are used in study, one is numerical and other is experimentation. Authors have used experimental data which is then validated by numerical analysis. For experimentation purpose, a rectangular beam is used with active length of 400 mm and different combination of width and
thickness. The material of beam is steel with usual material properties. The crack is open type with 1 mm width and is developed by wire cut method. The crack location ratio ranges from 2.5 to 50 per cent while crack depth ratio ranged from 0.15 to 0.7. Authors have presented the data for several combinations of crack parameters and have taken help of frequency ratio of healthy and damaged beams. The concluding remarks show that, for same crack location ratio and crack depth ratio, the value of frequency ratio is almost same with maximum error of 3 per cent.

In the current project work, crack detection in steel beams is studied. The study is divided into main two parts, one is healthy beam and then cracked beam. Further, the healthy beam study includes natural frequency analysis by the analytical, numerical and experimental approach. As the material of beam is kept constant throughout the project, the actual material properties such as density and modulus of elasticity are first determined experimentally same as Jinhee Lee and then considered throughout the study, so as to improve the accuracy of results. The cracked beam study includes single cracked beam analysis. This study is further divided into the crack location and crack depth determination. The concept of antiresonance is used to locate known and unknown crack while natural frequency is used to find crack depth. The combination of Jinhee Lee technique and antiresonance technique is the novelty of current work. The crack depths are varying in nature. The accuracy of current technique which was proposed in literature is tested and validated for new beam and crack configurations.

Healthy beam analysis

Mathematics and formulation. To find the natural frequency of beam, we use two approaches, i.e. strength of materials and vibration analysis approach (Figure 1). When we study the simple application of Euler–Bernoulli beam theory, we get that natural frequency of cantilever beam can be easily derived from slope-deflection theory. The basic equation for transverse free vibration of the cantilever beam can be expressed as:

\[ f = \beta^2 \times \sqrt{\frac{EI}{\rho A}} = (\beta L)^2 \times \sqrt{\frac{EI}{\rho A L^4}} \]  

(1)

Here, “f” is natural frequency in rad/s, “β” is constant to be determined from boundary conditions of the beam, E is the modulus of elasticity, I is area moment of inertia, ρ is material density and A is a cross-sectional area of beam, all are expressed in SI units. For cantilever beam with free vibrations, the values of β for first three natural frequencies of the beam are \( \beta_1 L = 1.8751, \beta_2 L = 4.6941, \beta_3 L = 7.8548 \) (Rao, 2004). The geometrical and material configuration of beams, which are used throughout the study either healthy or cracked, is shown in Table I, Data Book (1995). Thus, taking all these parameters in standard values, we can find out natural frequencies as shown in Table II.

Numerical study. It is always expected that whatever the results we are getting from an analytical study, we should verify it with some other study. This is the reason why

Figure 1.
A solid steel healthy beam with square cross-section considered
numerical study comes into the picture. The finite element analysis (FEA) approach is used for the numerical study of healthy cantilever beams. The structure is divided into the small finite number of elements. Hence the number of degrees of freedom also gets reduced. The mathematical treatment is applied only on such separate elements and then meshing of these individual elements is done to obtain the entire structure. In current work, commercial software package ANSYS is used:

- **Preprocessing:** First step is to prepare a drawing, i.e. model of the beam structure. Once the model is prepared, it is discretised into finite elements. The element used for the beam section is tetrahedron 10 node element. This is because the fine meshing can be done, maximum number of elements can be obtained and accuracy of results can be achieved. The testing with other elements than tetrahedron, has been done, and it is observed that meshing could not been done properly and result varies from required values.

- **Processing:** Here we simply solve the beam problem using ANSYS solver. After giving boundary and loading conditions, we apply modal analysis to obtain natural frequencies of beam.

- **Postprocessing:** The natural frequencies obtained from modal analysis are shown in Table II. The Figure 2 is representative of first mode shape and natural frequency of beam in ANSYS.

**Experimental testing.** The actual steel beam with the configuration shown in the table is tested on a dedicated experimental set-up developed in laboratory (Figure 3). The set-up offers the facility like variations in boundary conditions, different elements like beams, plates, shafts, variation in length and width. A commercial 4 - channel FFT analyzer of Adash VA4PRO model is used for the experimental study of cantilever steel beam. The natural frequencies can be easily extracted with FRF contour plots and are tabulated below. Maximum frequency is set at 800 Hz with number of lines of 1600.4 times pri-trigger is scheduled and its average is considered. The interesting part of the above three stages is to

<table>
<thead>
<tr>
<th>Geometric properties</th>
<th>Material properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Beam length</td>
</tr>
<tr>
<td>Steel C40</td>
<td>0.8 m</td>
</tr>
</tbody>
</table>

Table I. Geometrical and material properties of the beam used

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Analytical results</th>
<th>From current work</th>
<th>From literature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial study</td>
<td>Modified study</td>
<td>Initial study</td>
</tr>
<tr>
<td>First natural frequency (Hz.)</td>
<td>25.5911</td>
<td>25.2355</td>
<td>25.5495</td>
</tr>
<tr>
<td>Second natural frequency (Hz.)</td>
<td>160.1889</td>
<td>157.7220</td>
<td>159.65</td>
</tr>
<tr>
<td>Third natural frequency (Hz.)</td>
<td>448.3512</td>
<td>442.1207</td>
<td>444.91</td>
</tr>
</tbody>
</table>

Table II. Natural frequency of the healthy beam
compare and validate their results. This comparison and validation, shown in Table II, ensures the correctness of methods used and direction of study.

*Modification in actual beam properties – density and Young’s modulus.* Whenever we are dealing with the healthy beam, we must ensure that no crack is present on the surface of the beam. In current case, we use dye penetrant testing on the actual steel beam. The surfaces are thoroughly observed after testing and is concluded that the beam under experimental testing is really crack-free and hence results obtained from such healthy beam are true in sense. After this step, the technique of finding the actual Young’s modulus and density, which was adopted by Jinhee Lee, is used and tested. The actual density of beam
material is checked by measuring its actual mass and actual dimensions. This has given us the actual density of beam material as \( \rho = 7500 \text{ kg/m}^3 \). From the experimental study, we know the first three natural frequencies of the beam. We are using these values for finding modified modulus of elasticity as follows: First, obtain the first three natural frequencies extracted from FFT experimentation. They are shown in Table I. Second, use these values sequentially in equation (1). Solve them simultaneously to get the three values of Young’s modulus E. Take their average to get actual modulus of elasticity. Third, the actual modulus of elasticity is found to be 182 GPa. These values of density and modulus of elasticity, which are shown in Table I, are taken throughout the further study.

Single cracked beam analysis
The main objectives of current research work are to locate a crack, to find its severity and to verify the accuracy of the methodology adopted for this research by the numerical and experimental study. In current work, we have focused on single open surface crack on beam but the further study of double or multiple cracks can also be extended which is already underway. In actual practice, cracks in a structure like turbine blades or airplane wings are having the very small width and depth at the initial stage. Thus, we should focus on very thin cracks at the initial stage so that we can take corrective action and we can save the component failure.

Authors such as Ruotolo and Surace (2005), Owolabi et al. (2003) and Dilena et al. (2004), have concluded that notch and cracks have the same effect on vibration analysis and have given a rare attention on crack width. The saw cut or wire cutting cut can be adopted for a crack generation in the beam for study. There is a wide range of width used by researchers. As far as crack width is considered, an attempt has been made to keep it as small as possible.

Based on the laboratory resources available, we use the wire cutting method and the crack width is kept around 0.250 - 0.300 mm in current work. Crack depth ratio is the ratio of crack depth to the total beam depth. Very small crack depths are not so harmful from performance and safety point of view. Also, signature analysis from vibration output becomes difficult to distinguish. Hence the least crack depth in current research work is taken as 20 per cent (4 mm.) and a maximum value of 80 per cent (16 mm.). Maximum depth is selected because only to get clear vibration signature and significant reading changes in the analysis. As already stated in Table I, the length of the beam is selected as 0.8 m so that satisfying the Euler-Bernoulli beam theory. A similar configuration has been used by Lee (2009). In the case of single cracked beams, the crack location is at 400 mm from the fixed end as shown in Figure 4. In the other studies by researchers, they have used crack location ratio of around 30 to 60 per cent. With the same references, in the current paper, the first crack is located at 50 per cent from the fixed end of cantilever boundary conditions.

Numerical study. The single cracked beams are studied by first creating models in ANSYS software and finding their natural frequencies by modal analysis. The procedure is already explained in previous section. The location of crack is fixed but the depth of the crack is varied. Total six beams are created in FEA study, which are shown in Figure 4. Their modal analysis is done and natural frequency is noted. Figure 5 shows meshed model of five beams created in software (Figure 6).

Experimental study
To find the existence of crack (crack location). Current work is mainly emphasizing on feasibility and usefulness of technique for crack detection so that it can be easily used in industries. This is because it may not be possible all time to use expensive analysis software. In the current work, a simple concept of antiresonance is used for crack detection.
Figure 4.
Six steel cantilever beams with cracks with same location and varying crack depth ratios

Notes: (a) 20% (4 mm); (b) 30% (6 mm); (c) 40% (8 mm); (d) 50% (10 mm); (e) 60% (12 mm); (f) 80% (16 mm). Values in bracket shows crack depth, crack location = 400 mm

Figure 5.
Meshed model of cracked beam (20, 30, 40, 60 and 80%)

Figure 6.
Photographs of cracked beam

Notes: Crack depth ratios – (a) 40; (b) 60; (c) 80%
We know that in vibration, many terms are used like stiffness, compliance, impedance, mobility, acceleration which are derived from relations of particle movement such as displacement, velocity, acceleration. Similarly, antiresonance is a phenomenon of the frequency response of a structure under the application of force. The frequency at which the impedance has the largest magnitude or the mobility has the lowest magnitude is known as anti-resonant frequency. Many researchers used many techniques for crack detection. In antiresonance technique, no much mathematical calculation is needed. Simply from the frequency response curve obtained from the FFT analyzer during testing, one can easily draw the conclusion about crack existence. For executing this technique, same as Bannios et al. (2002), the driving points need to be shifted. Here, we shift the driving point at an interval of 50 mm along the length of beam starting from its fixed end. Thus, we have 16 driving points along 0.8 m. It is an obvious fact that results of the cracked beam are to be compared with the healthy beam, so we carried out the same driving point and antiresonance frequency measurement with healthy beam also.

In short, we find first resonant frequencies and first anti-resonant frequencies for both, healthy and single cracked beams. Following are FRF contour plots from FFT analyzer showing anti-resonant frequencies. These anti-resonant frequencies are extracted from responses and then plotted against driving point along beam length. This is very easy method for crack location. At the same time, natural frequencies are tabulated at different driving point locations and for varying crack depth. These tables are useful in crack severity determination (Figure 7 and Table III).

The graphs shown in Figure 8 are helping better for locating a crack. On the horizontal axis, distance from the fixed end of the cantilever beam is taken, while on a vertical axis, first antiresonance frequencies are taken for both, i.e. healthy and cracked beams. From graphs, it is clear that the nature of change of antiresonance with distance from fixed end is smooth for the healthy beam. But for the cracked beam, the nature of curve is not smooth. When the driving point is moving towards crack, the first antiresonance is almost a straight line. It means that from the fixed end to crack location, the first antiresonance almost remains constant. But once we cross the crack, there is a sudden jump or kink observed in the value of first antiresonance. The existence of kink in the value of first antiresonance is an indication of the existence of unknown or known crack. Thus, antiresonance is proved to be one of the effective tools to locate an unknown crack, rather it is simple to extract also. The requirement for this technique is to have the training of FFT. Also, for the healthy beam, we must have its whole data. Means for a new turbine blade, we must have its whole data before installation.

To find severity of the crack. Once we locate the unknown crack, the next activity is to find its severity, i.e. depth of the crack. For experimental purpose, three beams are taken with crack depth ratio of 40, 60 and 80 per cent. In the numerical analysis, we have found natural frequencies of cracked cantilever beams for crack depth starting from 20 to 80 per cent. In this numerical study, we have used natural frequency as a tool for finding an unknown crack depth. When we go through literature, authors such as Patil and Maiti (2003) have gone through a huge mathematical modeling and then found new parameter such as transfer matrix using natural frequency tool and then located the crack and found its depth. In current work, simple two concepts are used finding the crack depth. One is the frequency ratio and the second is the crack depth ratio.

“Frequency ratio” is defined as the frequency of cracked beam to the frequency of uncracked (healthy) beam. It is similar to Elshamy et al. (2018) and many other researchers. If we are dealing with numerical treatment, then both the frequencies in this ratio should be taken from ANSYS software only. But when we want experimental results, then frequency
obtained with FFT for the cracked beam is divided by frequency obtained with FFT for a healthy beam. So, this ratio can be used to compare cracked beam with healthy as well as to find crack depth. One more thing to note here is that this ratio is the ratio of two similar quantities. Hence it is non-dimensional. Few authors have termed it as non-dimensional.

Figure 7.
First antiresonance frequency plots from FFT analyzer

Notes: Crack depth ratios (a) 40, (b) 60; (c) 80%
frequency ratio or normalized frequency. In current work, the total beam depth is 20 mm. Hence when we say that crack depth is 20 per cent, it means that the depth of crack is 4 mm and so on.

To find the crack depth for an unknown crack, we have to correlate above two variables. For this, various methods are available, but here we have used “best fit” between them. The frequency ratios and crack depth ratios are obtained from Tables II and IV. For such best fit, we use frequency ratio plotted on the $y$-axis and crack depth ratio on $x$-axis. It is shown in Figure 9. The graph is showing a trend of change in frequency ratio as crack depth ratio changes. The reduction in the natural frequency with crack depth is obvious. But we are interested in the functional relationship between these two parameters. The best fit between them is expressed as:

$$y = -0.2117x + 1.04986$$  \hspace{1cm} (2)

Now equation (2) is expressing the best fit for the curve shown in Figure 9. This equation can be used to find any unknown value of $y$ if $x$ is known or an unknown value of $x$ if $y$ is known. Now experimentally when we take readings from FFT analyzer, we have the value of $y$ with us. We have used three beams with crack depth 40%, 60% and 80% per cent. The first resonant frequencies for these beams are already obtained experimentally. If we take the value of first natural frequency at 400 mm, this natural frequency for 40% crack depth is 24.50 Hz. The frequency ratio is then $y = 0.9703$. Then from equation (2), the value of $x$ is 0.3758. This is nothing but the crack depth obtained from experimental data. We know that the actual crack depth is 40% per cent, i.e. 0.4. Thus, the error in actual crack depth and measured crack depth is 6 per cent. Similarly, for actual crack depth of 60% per cent, the measured crack depth comes as 0.5633. Here the error in measured crack depth and actual crack depth is coming 6.1 per cent. Next further going, for 80% per cent case, the error in measured crack depth and actual crack depth is 11.3 per cent. Thus, the above analysis
Figure 8.
Experimentally tested changes in the first antiresonance along 0.8 m

Note: Crack location: 0.4 m from the free end

Table IV.
Natural frequencies of a single cracked cantilever beam using ANSYS for constant crack location but varying depth

<table>
<thead>
<tr>
<th>Sr. no.</th>
<th>Natural frequencies (Hz.)</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Second natural frequency</td>
<td>156.30</td>
<td>154.25</td>
<td>151.15</td>
<td>146.23</td>
<td>138.68</td>
<td>107.98</td>
</tr>
<tr>
<td>3</td>
<td>Third natural frequency</td>
<td>440.14</td>
<td>440.11</td>
<td>440.23</td>
<td>440.07</td>
<td>440.05</td>
<td>439.68</td>
</tr>
</tbody>
</table>
shows that the tool of natural frequency used for crack depth finding is very much suitable and found much accurate. The range of error obtained between actual and measured crack depth is 6 to 11.3 per cent. It means that on an average this method gives the idea about crack depth within the accuracy of 9 per cent (Figure 10).

Discussion of results obtained
During completion of the current project, several new concepts, new methodologies are learned in vibrations, FEA and crack detection. It has expanded the scope of the work. The interest was continuously increasing and many new activities were involved during the research period, which led to the learning of various out of scope techniques.

It has been found that, before starting actual work, the finding of actual density and modulus of elasticity was a helpful practice. Because of this step, it was simple to reach towards more accurate results in further analysis. It quite improved the novelty of method. Also because of this, when we were finding the difference in predicted and actual values for crack location and crack depth, this difference is found small.
Discussion on crack location

It has been observed that many authors have given antiresonance graphs obtained by numerical study, then they have predicted the value of anti-resonant frequency and from that, they have located the crack. But in current work, same technique is implemented experimentally. When the experimentation was going on, the same nature of graphs has been found and then it leads to the validation that the direction of work is correct.

The result of anti-resonance is useful to locate the crack. After going through the results obtained from anti-resonant frequencies, we can say that the actual crack location and measured crack location are very close to each other. In the case of 40 per cent crack and 80 per cent crack, the jump in anti-resonant frequency is exactly at the crack location. For 60 per cent crack, the actual location is 400 mm from the fixed end of the cantilever beam. But the kink or jump in anti-resonant frequency is obtained in the range of 400 to 450 mm. The error for a crack location using anti-resonant frequency is around 50 mm.

Thus, the accuracy of this method is fairly good. There is good agreement between literature results and results from current project work. Though the calculated and actual crack locations are maximum 50 mm away from each other, but we can concentrate only on that particular area and the whole beam need not be tested. Thus, one of the important results from this study is that we can find that affected area where a fault exists.

For locating the crack, the main indication is the kink or jump observed in anti-resonant frequency at crack location. For this, the driving point is shifted along the length of the beam. Before crack location, there is a smooth change in anti-resonant frequencies. But when we cross the crack, there is the sudden rise in frequency value. Such rise is not seen for the healthy beam, and it shows a smooth nature of the curve. This gives us an idea about the existence of crack. Also, such kinks in the graph are useful for locating any unknown crack. For this, the only important requirement is to read the frequency response curves carefully. The drawback of this method is only that the operator must have a training of FFT analyzer, and the confidence level should be high and is built through consistent practice.

One more thing to note here is that at the time of installation of any machine component such as a turbine blade, we have to go through the thorough numerical analysis. This helps to generate the database which will be required in further work.

Discussion on crack depth determination

In current work, the numerical and experimental both studies are combined and then crack depth has been found for single cracked beams. The first natural frequency for single cracked beams as well as healthy beams is found from the FEA approach using ANSYS software. Here the terms such as frequency ratio and crack depth ratio have been used. In this technique, the relation has been established between the frequency ratio and crack depth ratio. This relation can be used to find crack depths of known as well as unknown cracks when we use results from experimentation. When we plot results graphically, then it becomes easy to find crack depth ratio, by intercepting frequency ratio and crack depth ratio.

The difference between actual crack depth and calculated crack depth is found very small and is very close to the difference obtained by many authors from literature. It has been found that the measured crack depth is around ± 9 per cent different than the actual value. Like this, though we are not getting 100 per cent exact idea about the severity of crack depth, we have approached very close to the actual severity.
Conclusions
Steel can be selected as a material for study because of its wide usage and ease of study. Analytical study of the healthy beam is done on simple formulation from the strength of materials and vibration theory. For the numerical analysis, i.e. FEA study, ANSYS 14.0 software is used. Experimental results are obtained using self-designed and developed set-up and FFT analyzer VA4PRO model. Results from the analytical, numerical and experimental study are compared and found the best agreement between them. Results are also validated with the results from literature and found very close to current project work results. The health of uncracked beam is checked. This is to assure that the beam, to which we are calling healthy, is really uncracked. Dye penetrant test is applied, and it is proved that the beam is really crack-free. The actual density and modulus of elasticity of beam material have been found and it is different than the theoretical values taken before. Hence, the results from the previous study have been revised and compared, validated with literature. Again, new values found good agreement and are used for further study.

Three beams with single crack (40, 60 and 80 per cent) and cantilever boundary conditions are studied in experimentation, while more three beams are considered for FEA study (20, 30 and 50 per cent). To find the anti-resonant frequency driving point is shifted along the length of the beam and then the crack location is identified with great accuracy. It has proved that antiresonance is a simple and accurate technique to locate the cracks in the single cracked beam. It is not only helpful in current work but to locate the unknown cracks, this technique is very effective. For finding the crack depth, i.e. severity, the first natural frequency is used. Frequency ratio and crack depth ratio are related to each other, and this relation is found by best fit technique. Then the known and unknown crack depth is found in this relationship. The difference between measured and actual crack depths is found around 10 per cent. The proposed method gives an idea about initiation of crack in the beam and before severe propagation we can find its size.

Limitations and future research directions
The research is focused only on a single crack in a beam. Also, the material of the beam under study is only steel C40. The crack is on the surface and open breathing in nature. Apart from the terms used from vibration here, various other terms can be used for the study. Further work is already underway by same author to explore the applications of the methodology used in this study to different engineering areas. These include multi-cracked beams, composite materials, different boundary conditions of the beam, sub-surface cracks.

References


**Further reading**


**Corresponding author**

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An investigation of mechanical behavior of concrete containing crushed waste glass

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Abstract

Purpose – This paper aims to discuss the evaluation of the compressive and splitting tensile strength of concrete mixes containing different proportions of up to 20 per cent glass aggregate. Portions of sand in concretes with and without admixtures were replaced with measurements of glass aggregates.

Design/methodology/approach – “Glascrete” is a term used for concrete in which crushed glass is used as a substitute for all or part of the aggregates. Glass can be recycled many times without changing its properties, making it an ideal material in concrete. Overall, 144 cubes and 144 cylinders of glascretes were prepared with different admixtures and subjected to compressive and splitting tensile strength test.

Findings – A comparison with a 21-day control mix indicated that glass aggregates are replacing sand in concrete ranging from 5 to 20 per cent by volume, resulting in 3.8-10.6 per cent and 3.9-16.4 per cent fall in compressive and tensile strength, respectively. However, the use of mineral admixture improved the properties of the mixes at 3, 7, 14 and 21 days.

Social implications – Cities worldwide are congested, and even those with the best waste-management system would have issues with waste disposal after the year 2030. Consequently, waste management is a current issue for cities all over the world.

Originality/value – This study aims to evaluate the physical properties of mortar mixes that contain different volumes of waste glass as substitutes for fine aggregate with or without additives. Mineral additives are used to improve the mechanical properties of glascrete mixes in addition to its chemical resistance by absorbing the OH⁻ ions responsible for the possible alkali-silica reaction (ASR). It also reduces the adverse effects of mix-dimensional stability. Water-reducing admixtures are used to reduce the impact of the ASR by minimizing the amount of moisture in concrete, in effect decreasing the possible expansion of any produced gel. In this research, compressive and splitting tensile strength of concrete mortar containing waste glass of limited substitutions is evaluated.

Keywords Aggregate, Aggregate substitutes, Compressive and splitting tensile strength, Glascrete, Mineral admixture, Sustainable concrete

Paper type Research paper

Introduction
Cities worldwide are congested, and even those with the best waste-management systems might have issues with waste disposal in the coming decades. Consequently, waste management is a crucial issue for cities throughout the world. Several researchers have investigated methods for
resolving challenges and opportunities related to waste recycling (Mavropoulos, 2010). According to Parfitt, 2002 recycling reduces the shortages and demand for raw materials. In addition to reducing the amount of waste materials that have to be disposed of, the reuse of some waste materials on construction projects has reduced the cost of raw materials for new products. Vijayakumar et al. (2013) has indicated that glass waste or powdered glass have been reused as a partial substitute for aggregates in concretes. Other waste materials successfully reused in the construction industry include recycled asphalt, cement, bricks, plastic, steel and tires. Parfitt (2002), asserts that 1.2 tons of raw materials are conserved when over a ton of glass is recycled. Glass is one of only a few materials that can be reprocessed more than once without any change to its chemical properties because its structure is not altered when it is reprocessed. Glass products such as glass containers, flat bulbs, and cathode ray tubes have limited lifespan for their intended purposes. Therefore, they need to be recycled to help alleviate the problems at landfills. Although recycling is capital-intensive because of the amount of energy required, the carbon dioxide released into the atmosphere is less than producing new products from raw materials (Parfitt, 2002). The recycling of glass requires proper sorting, the removal of contaminants, stockpiling and recycling plants or facilities. Unfortunately, the scarcity of recycling plants restricts the use of waste glass in construction and not viable option. Oyekan (2007) at a conference in Singapore presented the concept of using glass aggregates to help in strengthen sandcrete blocks by first replacing sand and secondly partially replacing cement with crushed waste glass. The amount of crushed waste glass used to replace the cement ranged from 15 and 20 per cent, yet the concrete samples tested had strength increases from 30 per cent and 33 per cent, and 23 per cent and 74 per cent respectively. Jin et al. (2000), in the publication “Glascrete – concrete with glass aggregate,” discusses the use of glass aggregates as a sub-base material on some road projects, where aggregate (sand) was completely replaced with glass in concrete. Concrete containing recycled glass has a different appearance. It is smooth, it varies in color and it has reflective properties which makes it an attractive option in decorative applications such as masonry, wall partitions, tiles, panels, elevator panels, park seats and curbstones (Jin et al., 2000). Meyer (2003) and Concrete Technology Unit (2003) outlined the following beneficial properties of glass as a construction material:

- The rigidity of glass gives the glascrete abrasion strength which compares well with natural sand used in concrete building units.
- Glass has zero water absorption; so, it improves the workability of fresh concrete because of the reduction of water-cement (W/C) ratio without using water-reducing admixture (WRA).
- The tiny particles of crushed glass may have pozzolanic characteristics when used as a partial replacement of cement as compared to sand (natural stone). This property allows it to be used as a partial cement replacement. Thus, less cement is used when large volumes of concrete are required leading to economic benefits.
- The shades of colors and reflective properties of glass aggregate give it a good light reflection compared with conventional aggregates. Thus, it is useful in decorative applications and reflects lights during the night.
- Waste glass products are readily available, making glascrete a cheap material (economic advantage).

Purpose of the research
The purpose of the research was to evaluate the physical properties of mortar mixes that contain different volumes of waste glass as substitutes for fine aggregate, with or without
additives. Mineral additives are used to improve the mechanical properties of glascrete mixes in addition to its chemical resistance by absorbing the OH⁻ ions responsible for the potential alkali–silica reaction (ASR). It also reduces the adverse effects of mix-dimensional stability. Water-reducing admixtures are used to reduce the impact of the ASR by minimizing the amount of moisture in the concrete resulting in decreasing any expansion of the produced gel.

This research, evaluated the compressive and splitting tensile strength of concrete/mortar containing limited amount of waste glass of limited substitutions is evaluated. The research objectives were the following:

- investigating the effects on the properties of the glascrete mixes by adding four different volume replacements of up to 20 per cent of crushed waste glass as a partial replacement for fine aggregate;
- studying the impact of cement replacement on concrete mix properties using mineral admixtures; and
- evaluating the effects on concrete using a water-reducing admixture (WRA) and different mixes of concrete.

**Literature review**

This section presents a review of the current literature related to the use of waste glass in construction and non-construction applications, with specific emphasis on the use of waste glass as a fine aggregate and mineral additive in concrete. Crushed and graded glass cullet has been evaluated in construction and non-construction related applications. Shaopeng *et al.* (2003) asserted that crushed waste glass could be used in asphalt concrete (glassphalt) up to the size of 0.0048 m with an optimal replacement ratio of 10 per cent by weight of aggregate. Shaopeng *et al.* (2003) also discussed the performance of using glass regarding its strength index, stability at high temperatures and water volume. Sagoe *et al.* (2001) stated in their work that ground glass cullet, owing to its high abrasion resistance, has been used as an abrasive material in sandblasting for site cleaning and the removal of rust or paint. Glass cullet is not pervious and it has less than 1 per cent crystalline silica, so it presents no additional risk when compared with natural sand (Sagoe *et al.*, 2001; Wisconsin Department of Transportation).

According to a report written by South Dakota School of Mines and Technology, glass cullet is suitable for use as a backfill material with different levels of replacement up to 100 per cent. Owing to its zero water absorption and consolidation, it is suitable for use as a bedding material for pipes and paving stones. Crushed glass cullet is stable in moist environments, and proper compaction leads to no settlement, thus no rutting when it is used in road construction. Glass cullet can be used in concrete in three ways: as a coarse aggregate (gravel), a fine aggregate (sand) and in powdered form (mineral admixtures) (Sagoe *et al.*, 2001; Byars *et al.*, 2004). Crushed waste glass used to replace sand in concrete has the same characteristics as quartz sand, it has the same particle density and it is hard to crush.

Sagoe *et al.* (2001) argued that the use of a fine glass aggregate (with a particle size less than 0.0025 m) would not alter fresh concrete properties. However, the percentage of strength improvement follows a semi-linear relationship between 5 and 30 per cent glass replacement levels; there is a 5 per cent reduction in compressive strength at 5 per cent glass aggregate replacement by weight of sand and a 27 per cent reduction at a 30 per cent glass aggregate replacement. The reduction in strength is attributed to the mechanical properties of glass aggregate, rather than its chemical properties. Thus, the suggested ideal replacement of the
fine aggregate is 20 per cent by weight. In a study by Shehata et al. (1996), different glass aggregate replacements volumes of up to 20 per cent were evaluated, and the critical findings are as outlined:

- The use of a fine glass aggregate did not affect the physical properties of glascrete mixes as compared with the control mix. However, the 28-day compressive strength and tensile strength were below the control mix by 15 and 11 per cent, respectively; yet the compressive strength and tensile strength of the 20 per cent replacement gave values close to the control mix.

- The higher modulus of rupture values investigated for all glascrete mixes relative to the control mix indicated that an excellent interfacial bonding exists between the cement paste and glass aggregate. The glass aggregate acts as a crack arrestor, preventing cracks from spreading through the concrete structure.

Siddiqui et al. (2004) confirmed the above by performing a three-support point bending moment test on concrete blocks containing different sizes of glass aggregates. The load carried by these blocks increased gradually with an increase in the particle size of the glass aggregates. The route of the cracks is skewed due to the resistance produced by the glass aggregate. Naik and Kraus (1999) developed a flowable concrete by using recycled glass aggregate and fly ash. The two kinds of flowable concrete investigated were that with and without fly ash. Mixes were proportioned with 30 per cent to 75 per cent replacement by weight of sand with glass aggregate and fly ash. The results indicated that high compressive strengths were obtained for all of the mixes. It was also found that lowering amount of the fly ash and increasing the amount of glass led to a rise in bleeding and segregation. The permeability of the flowable glascrete also rises with increasing glass aggregate replacements. Glass cullet could be considered as a suitable substitute aggregate for producing flowable concrete. Naik and Wu (2001), in one study, replaced cement with fly ash up to 45 per cent replacement by weight. For each combination of cement and fly ash, up to 45 per cent by weight of fine aggregate was also replaced with glass, and compressive and splitting tensile strengths tests were performed for of the all mixes. The results indicated that, for every mix the compressive strength decreased with increasing amounts of glass aggregate. However, the same quantity of glass aggregate mixed with 15 per cent of fly ash as a cement replacement exhibited increased compressive strength at all ages. Mixes with a high amount of cement replacement (30 per cent and 45 per cent) showed lower compressive strengths at early ages, but during the late ages, the compressive strength increased, as compared to the control mix. Their findings indicated that for all the mixes the splitting tensile strength test was not affected much by the glass content. Replacing the cement with fly ash had the same effect on compressive and splitting tensile strength.

Dhir et al. (2004) investigated the use of waste glass as filler aggregate in concrete. In their quest, Dhir et al. (2004) discovered that 20 per cent by weight was replacement level that ensures stability of the fine aggregate. The percentage of glass aggregate suggested was the highest level of glass filler aggregate used in their research. In addition to using fine and coarse aggregates in concrete, several research investigations have demonstrated that glass powder could also be used in concrete. Many silica-based waste materials could be added to cement as pozzolanic additives. Fine particles of ground glass have non-crystallized silica that reacts with dissolved calcium hydroxide in moist conditions, subsequently forming hydrated compounds as pozzolanic materials (mineral additives). Examples are pulverized-fuel ash (PFA) or fly ash, ground-granulated blast furnace slag (GGBS), and silica fume (SF) (Shayan, 2004). In a research project conducted by
Vijayakumar et al. (2013), glass waste crushed into a fine powder was used to replace cement in percentages of 0.254, 0.508, 0.762 and 1.016 m concrete. The resulting product was tested for compressive, tensile, and flexural strength. The tests concluded that glass powder of particle size less than 75 μm could prevent alkali-silica reaction and can be used as partial replacement of cement because it compared well with traditional cement concrete up to 60 days of age. However, when used as coarse aggregate, the compressive strength drops because of a decrease in workability, which is a result of the flat and elongated property of glass (Cheeseman, 2011).

According to Sawant and Ghugal (2015), the production of cement results in heavy environmental pollution by releasing carbon dioxide into the atmosphere, therefore, researchers have been studying supplementing Portland cement with naturally occurring, manufactured, or manmade waste. As a result, pozzolanic materials such as fly ash, silica fume, metakaolin and blast furnace slag are blended with ordinary Portland cement to improve the mechanical properties of cement. Metakaolin has gained ground in recent years as a partial replacement for cement. Sawant and Ghugal (2015) affirms that the fineness of the metakaolin helps improve the varying mortar and concrete strength and other parameters.

Lalitha et al. (2017), in a review of strength and durability of recycled crushed glass replacing fine aggregates in concretes, indicated that the following are possible: fine aggregates can be replaced with crushed glass; the increment in strength may be attained when the replacement of the fine aggregates with crushed glass is up to 20 per cent; the increase in particle size of crushed glass increases with the alkali–silica reaction; thus, finer particle size coupled with mineral admixtures (fly ash) reduces the alkali–silica reaction; finally, pozzolanic properties continuously increase with decreasing sizes with the glass powder.

**Methodology**

Experimental work was conducted at the Civil Engineering Department concrete laboratory at North Dakota State University in Fargo, North Dakota. A total of 12 mixes containing different quantities of glascrete were evaluated to ascertain their engineering properties and behavior. Crushed waste glass was used as a partial replacement in fine aggregate (sand) in different quantities, with or without mineral admixtures.

A total of 12 mixes were used to achieve the set objectives of workability, fresh density, compressive strength and splitting tensile strength. Compressive strength measurements were performed on a total number of 144 mortar cubes and the splitting tensile strength test was conducted on another set of 144 cylinders of glascrete. The percentage of WRA was measured in a trial and error procedure using slump tests. Finally, the percentage of metakaolin was measured on 18 cubes. Figure 1 shows the research process.

**Cement/natural fine aggregate/glass aggregate (GA)**

The cement used was Portland cement Type 1. It was stored in a dry location to decrease the effects of humidity on the properties of the cement. Table I shows the chemical properties of the cement used throughout this study. The fine aggregate was commercial aggregates and it was not graded or specified; however, according to ASTM C136/C136M-14, the absorption is rated 1.3 per cent.

The glass aggregates used for the experiments had a particle size of 0.0025 m and the color was clear per the manufacturer’s specifications. The glass aggregate texture was the same as sand (aggregate). Therefore, there were no issues encountered during the tests. Partial replacement volumes of between 5 per cent and 20 per cent of glass aggregates were
adopted in place of sand. Before use, the glass aggregates were washed to reduce or eliminate the effect of constituents that could affect the setting and hardening rate of concrete. AASHTO T-27 was assumed during the research. Thus, the sample used was #30 (600 \(\mu m\)). In Table II provides the mechanical analysis provided by the manufacturer of the glass aggregate.

**Mineral admixtures**

Pozzolans (fine particle size) react with \(\text{CaOH}_2\) and water to form calcium silicate hydrates (C-S-H), similar to those formed by cementitious materials (Neville, 1996). Pozzolans materials produce the binding action in concrete that increases its density, with a reduction

<table>
<thead>
<tr>
<th>Chemical properties of ordinary Portland cement (Type I) – (C₃A) may not exceed 15%</th>
<th>Total alkali (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₃S (%)</td>
<td>C₂S (%)</td>
</tr>
<tr>
<td>55</td>
<td>19</td>
</tr>
</tbody>
</table>
in porosity and permeability, and it improves its strength and durability because of increased chemical resistance. Highly reactive metakaolin (HRM), was used as a mineral admixture. HRM is a reactive material produced from clay at high temperatures between 700-900°C according to the specifications. Figure 2 shows the materials used for the mixes.

**Determination of the optimum replacement of mineral admixtures**
The suitable percentage of mineral admixtures HRM-ASTM C 494/C 494 M-99 by weight of cement are 0, 8, 10, 12, 14, 16 and 18 per cent. Wild *et al.* (1996) established that replacing of 8 per cent of the cement in a system produces significant strength increases and provides adequate protection against corrosion. However, replacement above 20 per cent (Lalitha *et al.*, 2017), result in decreases in strength, but acclaimed replacements of 8 per cent to 20 per cent to continue to increase the strength of the system. All of the test mortars consisted of one-part cement or cementitious materials and 2.5 parts of sand by weight. The standards used for the concrete mixture were 1:1.5:3, 1:2:4 or 1:2.5:5. The mix ratio for this study was 1:2.5:5, of cement and sand with all the additives and without gravel. The water-cementitious material (w/cm) ratios were adjusted to obtain a good flow and workability by using a slump test. The concrete slump test is an empirical test that measures the workability of fresh concrete more specifically – it measures the consistency of the concrete in a specific batch. It is also used to determine consistency and ensure uniformity among different batches of concrete. The slump test is used because of the simplicity of the procedure and apparatus used for it. For each replacement level in the study, three

<table>
<thead>
<tr>
<th>Percentage passing #16 (1.18 mm)</th>
<th>100%</th>
<th>Percentage passing #16 (1.18 mm)</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 (850 μm)</td>
<td>99.9</td>
<td>50 (300 μm)</td>
<td>39.5</td>
</tr>
<tr>
<td>25 (710 μm)</td>
<td>99.4</td>
<td>60 (250 μm)</td>
<td>19.4</td>
</tr>
<tr>
<td>30 (600 μm)</td>
<td>98.5</td>
<td>70 (212 μm)</td>
<td>10.0</td>
</tr>
<tr>
<td>35 (500 μm)</td>
<td>90.7</td>
<td>100 (150 μm)</td>
<td>1.3</td>
</tr>
<tr>
<td>40 (425 μm)</td>
<td>77.5</td>
<td>120 (125 μm)</td>
<td>0.5</td>
</tr>
<tr>
<td>45 (355 μm)</td>
<td>57.1</td>
<td>140 (106 μm)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table II. Mechanical analysis of glass aggregate

Notes: (1) Portland cement; (2) fineaggregate; (3a) and (3b) highly reactive met kaolin (HRM and glass aggregate)
(0.1524 m) cube specimens were molded. After molding, the specimens were placed in a standard moist room at a maintained temperature of 23°C ± 2 and a relative humidity of approximately of 95 per cent for 24 ± 4 h. The cubes were then removed from the molds and placed in saturated water. The optimum replacement level was determined to be 12 per cent by weight of cement, as shown in Table III.

Water-reducing admixture (WRA)
The water-reducing admixture used in this study was POLYHEED 1020. It is a mid-range, water-reducing admixture. This product is a versatile and economical concrete plasticizer with a wide dosage range suitable for various applications. The properties of this product include improved workability without increased water, reduced water without loss of workability, increased strength, improved surface finish, and reduced shrinkage and creep. POLYHEED 1020 conforms to the requirements given in ASTM C 494/C 494 M-99 for type A water-reducing admixtures.

Optimal dosage of water-reducing admixture (WRA)
In four sets and all of the other mixes containing the water-reducing admixture, the optimum dosage of 1.2 per cent was used. The optimum water-reducing admixture was obtained by gradually increasing the dosage of the admixture and adjusting the W/C ratio to obtain the same workability when using the slump test method (Table IV). The percentage of water reduction for each mix was recorded. Consequently, at the maximum reduced value, no more water reduction was acquired. According to the product data sheet, the dosage of the water-reducing admixture should range from 0.5 to 1.1 per cent by weight. Based on the data sheet, the first trial mix after 0.0 per cent was started with a dosage of 0.6 per cent by weight. The dosage of the water-reducing admixture was increased by increments of 0.2 per cent as indicated in Table IV. The source water for all concrete mixes and curing was Fargo city water.

### Table III.

<table>
<thead>
<tr>
<th>% HRM by weight of cement</th>
<th>W/C or W/CM gives good flow and workability %</th>
<th>Compression strength at seven days (KN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.54</td>
<td>26,352.52</td>
</tr>
<tr>
<td>8</td>
<td>0.56</td>
<td>24,002.37</td>
</tr>
<tr>
<td>10</td>
<td>0.57</td>
<td>24,286.85</td>
</tr>
<tr>
<td>12</td>
<td>0.58</td>
<td>24,904.55</td>
</tr>
<tr>
<td>14</td>
<td>0.60</td>
<td>23,825.18</td>
</tr>
<tr>
<td>16</td>
<td>0.62</td>
<td>22,720.43</td>
</tr>
<tr>
<td>18</td>
<td>0.64</td>
<td>22,676.10</td>
</tr>
</tbody>
</table>

### Table IV.

<table>
<thead>
<tr>
<th>Dosage of %WRA by weight of cement</th>
<th>W/C ratio gives perfect flow</th>
<th>Water reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.54</td>
<td>0.0</td>
</tr>
<tr>
<td>0.6</td>
<td>0.48</td>
<td>11.1</td>
</tr>
<tr>
<td>0.8</td>
<td>0.47</td>
<td>12.9</td>
</tr>
<tr>
<td>1.0</td>
<td>0.46</td>
<td>14.8</td>
</tr>
<tr>
<td>1.2</td>
<td>0.45</td>
<td>16.6</td>
</tr>
<tr>
<td>1.4</td>
<td>0.45</td>
<td>16.6</td>
</tr>
</tbody>
</table>
Experimental work

Mix proportions
The concrete mixes were cataloged into four sets of 12 mixes (with all the details) as shown in Tables V, VI and VII.

The materials, mixing procedure, cleaning, oiled molds and casting, with all steps, are shown in Figures 3 and 4.

Flow test – ASTM C1611/C1611M
The workability test was performed using the slump test method. Slump concrete creates various shapes, which are called as a true slump, shear slump, or collapse slump depending on the profile of the slumped concrete. Only an actual slump is of use in the slump test; if a shear or a collapse slump result is obtained, a fresh sample is made and the test repeated. A collapse slump means that the mix is too wet or is a high workability mix. The slump of $0 - 0.0254\text{ m}$ is used for roads, a $0.01016 - 0.0381\text{ m}$ is for foundations with light reinforcement, $0.0508 - 0.0889\text{ m}$ is used for standard reinforced concrete placed with vibration and $> 0.1016\text{ m}$ is high workability concrete. The slump test is conducted right after mixing the concrete.

<table>
<thead>
<tr>
<th>Set no.</th>
<th>Designations</th>
<th>Mix description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C</td>
<td>Mix with cement and natural sand only</td>
</tr>
<tr>
<td>2</td>
<td>GA-5</td>
<td>Mix with cement only and 5% by volume of GA as a partial replacement for sand</td>
</tr>
<tr>
<td></td>
<td>GA-10</td>
<td>Mix with cement only and 10% by volume of GA as a partial replacement for sand</td>
</tr>
<tr>
<td></td>
<td>GA-15</td>
<td>Mix with cement only and 15% by volume of GA as a partial replacement for sand</td>
</tr>
<tr>
<td></td>
<td>GA-20</td>
<td>Mix with cement only and 20% by volume of GA as a partial replacement for sand</td>
</tr>
<tr>
<td>3</td>
<td>AGA-5</td>
<td>Mix with 12% by weight of Mineral admixtures (HRM) as a partial replacement for cement and 5% by volume of GA as a partial replacement for sand</td>
</tr>
<tr>
<td></td>
<td>AGA-10</td>
<td>Mix with 12% by weight of Mineral admixtures (HRM) as a partial replacement for cement and 10% by volume of GA as a partial replacement for sand</td>
</tr>
<tr>
<td></td>
<td>AGA-15</td>
<td>Mix with 12% by weight of Mineral admixtures (HRM) as a partial replacement for cement and 15% by volume of GA as a partial replacement for sand</td>
</tr>
<tr>
<td></td>
<td>AGA-20</td>
<td>Mix with 12% by weight of Mineral admixtures (HRM) as a partial replacement for cement and 20% by volume of GA as a partial replacement for sand</td>
</tr>
<tr>
<td>4</td>
<td>WR</td>
<td>Mix with cement, sand and 1.2% of WRA by weight of cement</td>
</tr>
<tr>
<td></td>
<td>WGA-20</td>
<td>Mix with cement, 20% by volume of GA as a partial replacement for the sand and 1.2% of WRA by weight of cement</td>
</tr>
<tr>
<td></td>
<td>WAGA-20</td>
<td>Mix with 12% by weight of Mineral admixture as a partial replacement for cement, 20% by volume of GA as a partial replacement for sand and 1.2% of WRA by weight of the cementitious material</td>
</tr>
</tbody>
</table>

Table V. Details of four sets of mixes

<table>
<thead>
<tr>
<th>Molds</th>
<th>Size(m)</th>
<th>3 Days</th>
<th>7 Days</th>
<th>14 Days</th>
<th>21 Days</th>
<th>Quantity(m$^3$)</th>
<th>Test Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cube</td>
<td>0.1524</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0.0425</td>
<td>CT</td>
</tr>
<tr>
<td>Cylinder</td>
<td>0.1016 * 0.2032</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0.0197</td>
<td>TS</td>
</tr>
</tbody>
</table>
The fresh unit weight for all mixes was determined using the following equation (ASTM C138/C138M):

\[ D_F = \frac{(M_C - M_M)}{V_M} \]  

Where:
- \( D_F \) = fresh unit weight of concrete (kg/m\(^3\));
- \( M_C \) = mass of mold and concrete (kg);
- \( M_M \) = mass of empty mold (kg); and
- \( V_M \) = Vol. of the mold (m\(^3\)).

**Test for hardened mortar – ASTM C780**

Two kinds of tests for hardened concrete were investigated; compressive and splitting tensile strength tests. The average result for three specimens was used for each test.
Compressive strength ASTM C39/C39M
The compressive strength test was conducted on 0.1524 m cube specimens using a compressive strength machine (Figure 5) with 250 k capacity at a loading rate of 113.398 kg/s. The test was conducted for 3, 7, 14 and 21 days.

Splitting tensile strength test – ASTM C496/C496M
The splitting tensile strength for all of the specimens was conducted according to ASTM C496/C496M on 0.1016 × 0.2032 m cylinders using the compression machine with a 250k capacity with a gradually loading rate-increasing rate of about 43.3592 kg/s up to a cubes’ failure point. The test was again carried out at 3, 7, 14 and 21 days and the splitting tensile strength was determined using equation (2) (ASTM C496/C496M).

\[ T = \frac{2P}{\pi DL} \]  

where

- \( T \) = splitting tensile strength (kg/m^2);
- \( P \) = maximum applied load indicated at failure (kg);
- \( D \) = diameter of cylinder (m); and
- \( L \) = length of cylinder (m).

Notes: (4) Layer casting; (5) compaction procedure; (6) leveled specimen
Results and discussion

This section presents a discussion of the results of the properties of both fresh and hardened glascrete. Table VIII presents the properties for fresh glascrete and the unit weight tests.

The results indicate a decrease in the density of the glascrete mixes when they are compared with the control mix, owing to the lower specific gravity of the glass aggregate in comparison to sand. The mineral admixtures mixes had lower densities relative to the same mixes without mineral admixtures. This decrease is also because of the lower specific gravity of those minerals compared to ordinary Portland cement (OPC). However, mixes containing water-reducing admixtures within in set 4 indicated higher fresh densities as compared with control mixes. This behavior may be caused by the advantage of the reducing the amount of water in the concrete mix by using water reducing admixtures.

Compressive strength test – ASTM C39/C39M

Compressive strength is regarded as one of the most important properties of hardened concrete. It is the primary property used to determine concrete quality in a relationship with developed technical standards. Thus, it is important to evaluate whether changes in the mix composition will affect the early and later compressive strength of concrete.

The variations in compressive strength with age for the control mix and the mixes containing 5, 10, 15 and 20 per cent of glass aggregate as a partial replacement for sand and the comparison between the values of the compressive strength for the same mixes is shown in Figures 6.

The use of glass aggregate negatively influences, and slightly reduces, the compressive strength of concrete at all ages. The negative impact increases with the percentage increase in glass aggregate replacement with the highest reduction occurring in sample GA-20 and least in GA-5. The rough surface of sand gives it a higher strength over the relatively smooth, flat and elongated surface properties of glass (Cheeseman, 2011). The reduced compressive strength is due to lower adhesion and bonding strength between the glass aggregate and the cement paste. The only exception is a 21-day, GA-20 mix, which gained a higher compressive strength over the mixes for GA-10 and GA-15 of the same age. The transformation is caused by the pozzolanic reaction (fine glass particles) prevailing over the adverse effects of the glass aggregate texture. All of the mixes had improved strength with increasing age. Specifically, the compressive strength showed an overall increase with age with the percentage increase in the amount of glass aggregate. The percentage increase in

<table>
<thead>
<tr>
<th>Set no.</th>
<th>Details</th>
<th>Designations</th>
<th>Unit weight (Kg./m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control Mix</td>
<td>C</td>
<td>2,297.43</td>
</tr>
<tr>
<td>2</td>
<td>Mixes with cement only and glass aggregate (GA) as a partial replacement for sand.</td>
<td>GA-5, GA-10, GA-15, GA-20</td>
<td>2,242.07, 2,103.67, 1,992.95, 1,826.87</td>
</tr>
<tr>
<td>3</td>
<td>Mixes with 12% by weight of the mineral admixture (HRM) as a partial replacement for cement and (GA) as a partial replacement for sand.</td>
<td>AGA-5, AGA-10, AGA-15, AGA-20</td>
<td>2,186.71, 1,882.23, 1,799.19, 1,771.51</td>
</tr>
<tr>
<td>4</td>
<td>Mixes with cement, sand, and 1.1% of WRA by weight of cement, and 20% by volume of GA and 12% of the mineral admixture (HRM)</td>
<td>WR, WGA-20, WAGA-20</td>
<td>2,325.11, 1,882.23, 1,854.55</td>
</tr>
</tbody>
</table>

Table VIII.

Fresh unit weight for all mixes
compressive strength values between 3 and 21 days for mixes C, GA-5, GA-10, GA-15, and GA-20 are 41, 65, 60, 58 and 67 per cent, respectively. The difference is attributed to the pozzolanic reaction of the glass aggregate and up to 20 per cent replacement in concrete (Lalitha et al., 2017).

The compressive strength improvements for set 3 mixes are shown on the plot in Figures 7. These mixes contained the same glass aggregate replacement as set 2, with the addition of 12 per cent by weight of HRM as a partial replacement for the cement.
The following lists the results obtained from the experiments:

- Generally, all mixes within sets one and two showed a significant improvement in compressive strength with age; however, in set 2, the reverse was observed between 14 and 21 days for AGA-20. The observation may be because of an error in the data collection on the sample. Also, there is an observable weak bond strength and lower adhesion between the glass aggregate and the cement paste. The reduction in compressive strength increases with higher amounts of glass aggregate.

- Mineral admixture mixes in set 3 showed a reduction in compressive strength at an early age (three and seven days) relative to the same mixes in set 2 owing to less cement and more water content in these mixes to obtain the same workability. The w/cm ratio was 54 per cent in set 2 and it increased to 58 per cent in set 3.

- At 14 and 21 days, the compressive strength values for the mixes with mineral admixtures improved as compared to set 2 mixes, and the control mix. This was due to the pozzolanic reaction of both the mineral admixtures and the fine particles of GA, which reacted with the calcium hydroxide, producing an additional gel and reducing the number of voids in the mortar. On the other hand, set 3 showed unexpected reductions in compressive strength at age 21 days when compared with the age 14-day mix, a behavior which could be attributed to micro-fracturing occurring due to the different processes in the samples in this mix.

The improvements in the compressive strength for the WRA mixes within set 4 are shown in the plot in Figures 8. WRA mixes show significant improvements in compressive strength when compared to the same mixes without the water reducing admixture at all ages. This may be due to a reduction in the W/C ratio. For instance, at three days, the percentage increases in compressive strength for WR, WGA-20 and WAGA-20 relative to C, GA-20 and AGA-20 were 26.2, 50.5 and 75, respectively.

Mixes WR and WGA-20 in set 4 are indicative of the significant individual effect of WRA on compressive strength, which is attributed to the lower void content, and a more homogenous and consistent structure. Meanwhile, WAGA-20 shows the combined effect of WRA and minerals (HRM) on compressive strength relative to mix GA-20. The combined effect of WRA and the minerals produces a stable structure and decreases voids more than the individual effect of any one of them. Figure 9 shows the compressive strength development for the control mix and all of the mixes in sets 2, 3 and 4.
Splitting tensile strength test
The splitting tensile strength test was used to investigate the impact of glass aggregate on the adhesion and bond strength at the interfacial transition zone. The splitting tensile strengths for all mixes after being cured for 3, 7, 14 and 21 days are presented in Figure 10.

The results of the experiments conducted for this research project indicate the following:

- There was a significant increase in splitting tensile strengths for all of the mixes (both the control and admixture mixes) with age due to the process of hydration, which reduces permeability and improves the transition zone.

- There was a reduction in the splitting tensile strengths for all glascrete mixes within set 2 and set 3 with increasing glass aggregate replacement. This is due to weaker
bond strength between the glass aggregate and the cement paste compared with bonding in the conventional mix.

- By using the mineral admixture (HRM) in set 3, the transition zone improved, thereby, increasing the tensile strength of the HRM mixes within set 3. Although it showed lower initial strength values (up to the seven-day age), as compared to the control mix and the same mixes within set 2 (because of lower cement content), HRM mixes still developed higher strength with time under moist curing conditions. At age 14 days, HRM mixes improved the splitting tensile strength values to the values of the control mixture, and at 21 days, the values were almost higher than the control mix. This shows the benefit of the pozzolanic reaction of HRM.

- The results for the WRA mix within set 4 shows improvement in the splitting tensile strengths at all ages. This improvement is due to the reduction in the W/C ratios and to the uniform distribution of the hydration products in the mortar system leading to a matrix with minimum porosity. For example, the percentage increases in splitting tensile strength at the seven-day age for WR, WGA-20 and WAGA-20 as compared with mixes R, GA-20 and AGA-20 are 6.4, 27.6 and 33.5 per cent, respectively.

Conclusion

This study was conducted to investigate the characteristics and impact on the properties of mortar mixes:

- Containing four different volume replacements (5, 10, 15 and 20 per cent) of crushed waste glass as a partial replacement for sand.
- Replacing part of the cement with locally available mineral admixtures (metakaolin and HRM) and glasses with or without a water-reducing admixture.

The conclusions for the investigations are following:

- The use of glass aggregate (GA) as a partial replacement for natural sand does not reduce workability up to the specified range of replacement (20 per cent), even when the glass aggregate is substituted on an equal volume basis and has similar surface area.
- The use of glass aggregate as a partial replacement by volume for sand reduced the fresh and air-dry densities as the glass aggregate replacements were increased because the specific gravity of glass was lower than the specific gravity of sand.
- Glascrete mixes with fine glass aggregate replacement up to 20 per cent did not cause a reduction in the compressive strength.
- At age seven days, the reduction in compressive strength ranged from 9.1 to 20.8 per cent for mixes with glass aggregate replacement ranging from 5 to 20 per cent by volume of fine aggregate. The reduction in compressive strength might be due to a weak bond between the cement paste and the glass aggregate caused by the smooth surface of the glass.
- Glascrete was just as brittle as traditional concrete because concrete is a compression member, not a tension member.
- The splitting tensile strength for glascrete mixes was slightly lower than the control mix because of the lower adhesion and bond strength between glass aggregate and cement paste.
The percentage reduction in splitting tensile strength for the glascrete mixes with different glass aggregate replacements ranged from 9.1 to 20.8 per cent at seven days and from 3.9 to 16.4 per cent at 21 days relative to the control mixes.

The use of the mineral admixture (HRM) in different ratios as a partial replacement by weight of cement does significantly affect a mix’s workability.

Highly reactive Metakaolin produced lighter mixes due to the specific gravity of the mineral admixture is lower than the specific gravity of Portland cement. These effects varied according to the type, dosage, and fineness of mineral admixtures.

Cement replaced by 12 per cent highly reactive metakaolin increased the water requirement of the glascrete mixes by 6.7 per cent relative to the control mix.

The use of a water-reducing admixture produced a significant reduction in W/C ratios ranging from 7.4 to 16.7 per cent varying by the mix ingredients relative to the control mix.

The water-reducing admixture increased the mix density because of the uniformity of the mixture, the stable structure of the mortar and all of the voids in the mix were filled by the small particles of glass and pozzolanic material.

The mineral admixture (HRM) used throughout this study improved the compressive strength of the glascrete mixes and produced mixes with compressive strength values close to the control mix, especially during the later ages, because the small particles of glass reacted as a pozzolanic material with cement.

The use of 1.2 per cent water-reducing admixture by weight of cement significantly improved the compressive strength at all ages because of the combined influence of the mineral admixture with the water reducing agent.

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Abstract

Purpose – The purpose of this study is to address challenges in the current information exchange process between building information modelling (BIM) and facilities management (FM) systems and to propose a workable solution. This study’s objective is to identify the information exchange requirements and to develop methods for seamless information flow between building information models and FM systems.

Design/methodology/approach – Data collection and analysis was based on an extensive literature review of similar studies followed by a questionnaire survey with a total of 112 participants and 2 focus groups with a total of 12 participants to validate the conceptual framework. The outputs of the survey analysis formed the background of the proposed framework to streamline information exchange process between building information models and FM systems.

Findings – The study findings form a foundation for enabling the integration of various data sources including building information models. Such integrated platforms will enable automated information exchange between the various data sources and FM systems. The study also provides key information requirements sources to complement the existing construction operations building information exchange information and to support standardization for information exchange process.

Originality/value – The contribution of this study is the identification of information exchange requirements and sources to enable seamless information flow between BIM and FM systems. The study findings will also lay the basis for research studies using the developed framework context to enable the identification of specific data outputs for FM systems inputs.

Keywords Interoperability, Information exchange, Building information modeling (BIM), Construction operations building information exchange (COBie), Facilities information systems, Facilities management (FM), Interoperability, Industry foundation classes (IFC)

Paper type Conceptual paper

1. Introduction

During the operations and maintenance phase, facilities management (FM) teams often spend a considerable amount of time and effort collecting information in the form of electronic data and hardcopy documents. Employees engage in constant redundant activity searching for, sorting, validating and recreating information (Brodt, 2013). The

The authors would like to acknowledge the help and support of the BIFM in facilitating the focus groups workshop and the industry practitioners who participated in the research questionnaire survey.
National Institute of Standards and Technology (NIST) reported that two-thirds of the projected $15.8bn lost in the USA capital facilities industry was associated with inadequate interoperability during the operations and maintenance (O&M) phase. Losses because of poor interoperability resulted from the expenses of manual data re-entry, data verification, redundancy and wasted labor time looking for data that were often unavailable. Minimizing the effects of interoperability problems requires a seamless electronic data exchange to provide FM teams with a comprehensive and accurate database (Gallaher et al., 2004).

Building information modelling (BIM) can provide a data conduit and repository to support O&M activities (Sabol, 2013), but it is not sufficient in itself to mitigate the costs of faulty interoperability. There is a need for a common data model or schema for BIM data models to be interoperable with FM systems. PAS1192-3:2014 specifies an information management methodology for the O&M phase of building assets based on open BIM standards – Industry Foundation Classes (IFC) and Construction Operations Building information exchange (COBie) (BSI 2014a). The PAS1192-3:2014 focuses on the early engagement of FM team to ensure that facilities information requirements are considered from the early stages of the construction projects (BSI 2014a). Information in BIM models should reflect the Employer Information Requirements (EIR) which should be specified in the Asset Information Requirements (AIR) so that at the handover stage, handover data can be an output for FM systems input (BSI 2013). Several standardization efforts are proposing the use of BIM capabilities as a data conduit to support facilities information management such as BS 1192-4:2014 which supports facilities information exchange requirements using construction operations building information exchange (COBie) (BSI 2014b). COBie works like a filter that selects and arranges only necessary non-geometric information for the management and operation of a building into ten main categories: facility, floor, space, zone, type, components, system, spares, job and resources. COBie is a repetitive process, with four defined data drops taking place at crucial stages of the project life cycle to capture the required and available data for FM (East and Carrasquillo-Mangual, 2013).

There are various ways that COBie information can be exported from BIM models. Regardless of which tool is used to compile and create the COBie spreadsheet, one of the following principles will be adopted:

- COBie data are exported directly from BIM models using third-party add-in applications (such as the Autodesk COBie Extension for Revit).
- IFC data can be exported from BIM models and the COBie spreadsheet can be extracted as a “View Definition” from this data set; in many cases, the IFC format would be an acceptable method providing the COBie data (East and Carrasquillo-Mangual, 2013).

However, the BIM authoring products that export COBie data automatically and generate COBie spreadsheet are inherently limited in generating all the FM-required data, as a manual data entry is still required to enter data such as periodic preventive maintenance (PPM) schedules (Lee et al., 2013). Building such a database via manual data entry from individual stakeholders is costly and rarely achievable (Brodt, 2013). There needs to be a solution for the easy transfer of facility-maintained asset data into FM systems. In this study, we aimed to develop a conceptual framework for seamless data exchange between BIM and FM systems by incorporating data from BIM models and from various other data sources to generate a rich, interoperable data format that includes the required FM information.
2. Research background and related studies

There is no doubt that the proliferation of advanced computerization is yielding business benefits that are valued by the construction industry. Automation within the BIM–FM integration process will revolutionize how buildings are conceived, developed, built and used. However, there are some challenges of integrating BIM in FM practice that require innovative solutions to transform industry practice (Pärn et al., 2017). The opportunity to enhance facilities information management performance using BIM-rich semantic data is lost because of the existing gaps in software interoperability when transitioning data between as-built BIM and FM systems (Pärn et al., 2017).

Realizing BIM’s capabilities to support FM activities needs extensive software development to facilitate information exchanging between as-built BIM and existing FM systems (Gao and Pishdad-Bozorgi, 2019).

The inherent power of BIM for FM is mainly associated with streamlining information flow between the project stakeholders during the facility lifecycle and facilitating information handover to FM teams (Matarneha et al., 2018; Reza Hosseini et al., 2018). Yet information flow among project stakeholders is neither automated nor seamless. There are still technical issues to be overcome: mainly identifying the required FM information for data exchange purposes and boosting interoperability between BIM and FM systems (Gao and Pishdad-Bozorgi, 2019; Matarneha et al., 2019; Yalcinkaya and Singh, 2019). Although standard data formats are capable of exchanging data between different platforms, particularly IFC and COBie schemas, the data exchange process between BIM and FM systems using open standard data formats is not a straightforward process. For example, the integration between BIM and the computer-aided facility management (CAFM) system has been actively criticized for inadequate data interoperability, particularly the inability to transfer semantic FM information properly (BIFM, 2013).

Studies in this research have shown that many comprehensive systems are developed on the foundation of BIM-based facility database, which allows new functionalities such as visualization and data accessibility to perform various analysis and automate some of the O&M activities (Gao and Pishdad-Bozorgi, 2019). Yet studies that investigate interoperability solutions between BIM and FM systems are scarce (Reza Hosseini et al., 2018; Gao and Pishdad-Bozorgi, 2019; Matarneha et al., 2019). There is a need to understand the underlying information exchange requirements between BIM and FM systems and standardizing a process for information exchange between BIM and FM systems (Kasprzak and Dubler, 2012; Nical and Wodyński, 2016; Pärn et al., 2017; Gao and Pishdad-Bozorgi, 2019; Matarneha et al., 2019).

2.1 Identifying the information required for facilities management

Today’s facilities are highly sophisticated and the need for available, reliable information for O&M activities is vital (Jordan, 2010). The key challenge for an FM team is to obtain accurate, real-time data in a complete database to perform daily activities and to provide senior management with reliable information for decision-making (Atkin and Brooks, 2009; Pärn et al., 2017). Currently, there are a variety of technology platforms, data repositories and databases such as computerized maintenance management systems (CMMS) that are used for these purposes in various facilities. In a typical FM practice, data are extracted from hardcopy construction documents or electronic data such as .pdf files and is re-entered manually into a CAFM/CMMS system (Teicholz, 2013). The concept of extending BIM implementation through the O&M phase is simply to reduce the O&M costs and reap the real benefits of BIM capabilities. However, in most current practices where BIM is implemented to support FM operations, FM teams do not use BIM models because they
either do not include the required FM data or the models contain a huge amount of superfluous data which makes the data exchange process tedious and overwhelming (Sabol, 2013). Hjelseth (2010) stated that “an overload of information causes a lack of purpose, and therefore what could be information, is simply unused data”. This necessitates a pragmatic approach to identify the required information and to collect it from the project stakeholders in a way that FM teams can use efficiently.

Recent studies have focused on very specific information requirements by identifying the required information of: healthcare facilities (Lucas and Thabet, 2013; Irizarry, 2014), HVAC systems (Hu et al., 2016; Yang and Ergan, 2017; Hu et al., 2018) and the building handover process (East et al., 2013; Cavka et al., 2015; Mayo and Issa, 2016; Cavka et al., 2017; Thabet and Lucas, 2017). Only one article was found that focused on creating a generic set of information requirements for a successful information exchange process (Farghaly et al., 2018). Other authors in this area proposed an information classification and prioritization methodology (Rodriguez-Trejo et al., 2017; Reza Hosseini et al., 2018). There remains a lack of holistic guidance that encapsulates all the information exchange requirements between BIM and FM systems (Matarneha et al., 2019).

2.2 Interoperability and data exchange open standards
Interoperability is the capability to exchange data among different software programs to enable automation and to reduce the need for manual data entry (Eastman et al., 2011). Because of the wide range of BIM and FM platforms, interoperability between these platforms remains one of the key challenges in using BIM in FM practice (Kasprzak and Dubler, 2012; Kassem et al., 2015; Leite et al., 2016; Nical and Wodynski, 2016; Pärn et al., 2017; Gao and Pishdad-Bozorgi, 2019; Matarneha et al., 2019). There have been various recent attempts to improve interoperability by introducing different universal data standards such as the IFC and XML schemas and structured specifications such as COBie (Azhar et al., 2012; Yalcinkaya and Singh, 2019). Many countries and organizations have adopted the use of open BIM standards and data specifications in their project handover and O&M phase. For instance, the UK Government adopted COBie as the data exchange schema to support its BIM Level – two strategies (Kassem et al., 2015). However, these efforts represent only the first step in streamlining information flow throughout the building lifecycle. There are compelling reasons for moving forward with more pragmatic strategies to implement BIM in FM practice, but many stumbling blocks remain. One of these is the narrow use of open standards to identify the information required for FM (Patacas et al., 2015). Currently, the industry is more than ever aware of the need to remove these impediments to FM information requirements, data exchange and interoperability to extend BIM implementation to the O&M phase. However, problems related to BIM-enabled data exchange using open standards currently remain to be resolved (Cavka et al., 2017).

Recent research first focused on interoperability and data exchange to assess BIM open standards and data specifications using a case study approach (Patacas et al., 2015; Borhani et al., 2017; Pishdad-Bozorgi et al., 2018), then BIM open data specifications (COBie) were tested in the building handover process (East et al., 2013; Thabet et al., 2016; Yalcinkaya and Singh, 2019). Finally, BIM open standards (IFC) were used to capture and exchange facility data using different technologies such as a barcode system, digital sensors and augmented reality (Lin et al., 2014; Lee et al., 2016; Shalabi and Turkan, 2017). Background research showed that the process of transferring data from BIM data models to FM systems was not a straightforward process because software interoperability remained a substantial challenge (Nical and Wodynski, 2016; Gao and Pishdad-Bozorgi, 2019; Matarneha et al., 2019). Furthermore, the literature showed that the gap between BIM and FM systems in
terms of data exchange and interoperability still existed. Bridging this gap will require more research to provide a standardized processes and best practices method for seamless data exchange between BIM and FM systems. Our study summarizes the outcomes of research to identify the current gaps in interoperability and data exchange between BIM and FM platforms and proposes a conceptual interoperability framework for seamless data exchange between BIM and FM systems.

3. Research methods

The main purpose of this research was to tackle the challenge of improving the current information exchange process between BIM and FM systems. To achieve this aim, we used a mixed method approach to identify the information exchange requirements:

- an extensive review of related literature to identify the current state of BIM implementation in FM with focus on the information exchange process between BIM and FM systems;
- a questionnaire survey distributed to BIM practitioners in the UK with the goal of understanding the current state of facilities information management in BIM-based projects and to identify information exchange methods, tools and challenges; and
- two focus-group workshops facilitated by the British Institute of Facilities Management (BIFM) for the purpose of validating the developed theoretical framework of information exchange between BIM and FM systems as shown in Figure 1.

![Flow diagram of research design and methods](image-url)
A total of 112 BIM practitioners completed the on-line questionnaire survey and 12 FM practitioners participated in the focus groups.

4. Research results
While our overall intention in data collection was to tackle the challenges in the current information exchange process between BIM and FM systems, our views on the importance of having a seamless information exchange process between BIM and FM systems were collated. The survey questions were exploratory in nature to generate general understanding using closed questions to identify information exchange methods, challenges and requirements. However, BIM professionals who used/or are using BIM for FM were given the opportunity to add lessons learned from their experience using an open questions. Participants were selected based on their experience in using BIM in their construction projects and their knowledge about BIM benefits for FM. The on-line questionnaire was prepared using the SMARTSurvey service and posted to related BIFM and LinkedIn professional groups such as: BIM for FM, BSIGroup, BIM Group and BIM Task Group.

The two focus group meetings were conducted with 12 FM practitioners. The aim of the first focus group was to verify the proposed information exchange requirements proposed in the primary conceptual framework, while the second focus group validated the overall developed framework of information exchange between BIM and FM systems. Both focus group meetings were analyzed using content analysis and Nvivo software.

4.1 Questionnaire results
Based on an extensive literature review, a series of questions under four themes was used in a questionnaire to collect perspectives from BIM practitioners to understand the state of information exchange between BIM and FM systems. The questionnaire was available online from January 19th, 2018 until March 31st, 2018 and 112 responses were collected. Responses were analyzed using SPSS for the descriptive statistics and Nvivo for the analysis of the qualitative open questions responses; results are presented in the following sub-sections.

4.1.1 Demographic distribution. Practitioners in the construction industry in the UK were the main respondents to our questionnaire. Among the 112 participants, contractor and FM organizations were the greatest contributors with 26 per cent, followed by BIM consultants, technical engineers and architects with 21, 12 and 5 per cent, respectively. At the time of the questionnaire, 59 per cent of the respondents had been working in the construction industry for more than 10 years. The majority (81 per cent) had never worked on any project where BIM was used to support FM operations, but they are aware of BIM capabilities to support FM practice; only 19 per cent of the total had worked on at least one project where BIM was used to support FM. However, all respondents used BIM in different phases of the project lifecycle and were aware of BIM capabilities for FM. Participants were asked if they had knowledge about BIM capabilities for supporting facilities management practice, and all those who answered "NO" were disqualified from participating in the questionnaire survey.

4.1.2 Building information modelling application areas in facilities information management. As this study focused on leveraging BIM in facilities information management, the respondents were requested to choose potential application areas that BIM, with its capability as a data conduit, could bring value to. A substantial number of responses strongly agreed that BIM could enhance building handover processes (86 per cent), support facilities systems (67 per cent) and facilitate creation of a registry of digital assets (62 per cent) as shown in Figure 2. This is an important finding because it
demonstrated a general understanding that BIM was capable of acting as a data conduit to capture, collect and retrieve all information about a facility and its components during its lifecycle.

4.1.3 Challenges and implications. When BIM is used to support facilities information management, facility information can be captured, collected and retrieved throughout the building lifecycle and then used in a more automated and efficient way to support FM systems. However, some challenges still exist in using BIM as a database to support facilities information management. Among the respondents, 74 per cent agreed that poor interoperability between BIM and FM systems was a key challenge hindering BIM implementation in facilities information management. This was followed by the lack of a clear, standardized information exchange process (55 per cent) and the lack of clear information requirements (49 per cent) for BIM models to support facilities information management (Figure 3).

4.1.4 The current state of handover processes for building information modelling-based projects. The building handover process is critical to provide owners and facility managers with all information about the facility and its components. To understand how information is delivered to owners and facility managers in a BIM-based project environment, survey-takers were asked to select the deliverables they were required to provide at the building handover stage. As shown in Figure 4, the results indicated that the most frequent response was electronic copies in the form of pdf documents and CAD drawings (94 per cent), followed by native, as-built BIM models (91 per cent). With the adoption of BIM in construction projects, the need for non-geometric information delivery in the form of COBie...
spreadsheets becomes necessary; however, only 40 per cent of respondents indicated that they were asked to deliver COBie spreadsheets among other handover deliverables. On the other hand, 58 per cent of those surveyed indicated that a paper copy of construction documentation was required at the handover stage. Only a small percentage of respondents (15 per cent) indicated that an IFC file was required among the deliverables.

4.1.5 Information exchange methods between building information modelling and FM systems. A clear information exchange process is integral to a unified source of facility information that is collected during the different phases of the construction project. Respondents who were using BIM for FM (19 per cent) were asked to select the information exchange method they used to transfer information between BIM and FM systems. Figure 5 shows that about one-third of the respondents (32 per cent) said they did not know because they were still working on BIM models and had not reached the stage of transferring data to FM systems at the time of the survey. Among the other responses, 29 per cent of participants used manual data entry, while 24 per cent used COBie spreadsheets as tools to transfer facility information from BIM models to FM systems. Meanwhile, 9 per cent of the respondents used a middleware layer and 5 per cent used IFC files to transfer information between BIM and FM systems.

Respondents were asked whether they agreed that BIM models included all required facilities information: 89 per cent disagreed, 9 per cent neither agreed nor disagreed and 2 per cent said that BIM did include all required facilities information. Respondents were asked further to list the information that was still required and could not be included in BIM models. Most said that information related to maintenance and spare parts was usually not included in BIM models; and, even if there were a process for including this type of information, the existing COBie add-in applications do not support the generation of such data. Other respondents noted that the manufacturing information was usually not included in as-built BIM models, as manufacturers did not provide objects for BIM inclusion. Survey-takers were asked to select other required data sources for facilities information

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Figure 4. Handover deliverables for building information modelling-based projects

Figure 5. Information exchange methods between building information modelling and facilities management systems
management and the majority of respondents stated that the spares log and the manufacturers’ product data sheets were the most wanted external data sources at 92 and 86 per cent, respectively (Figure 6).

5. Discussion
Data analysis results confirmed the value placed by industry practitioners on the necessity of having a standardized information exchange process between BIM and FM systems and how specific asset information requirements are needed to reduce the redundancy of generating BIM outputs that do not match the FM system inputs. Moreover, questionnaire results revealed that COBie add-in applications do not generate a full, rich COBie spreadsheet and require manual data entries for maintenance-related data. For example, the COBie toolkit for Revit can generate 10 sheets of the required 18 sheets, but the most important data related to asset maintenance are not included, as this COBie add-in does not generate Spare, Resource and Job sheets. Moreover, the questionnaire results revealed that in the most current practice, manufacturers are not ready to provide objects for BIM inclusion, which means that BIM as-built models do not include the manufacturers’ product information, and FM teams have to collect this type of information from various sources. Building such a database by individual keystroking data entry is costly and rarely achievable. There should be an efficient process for manufacturers, suppliers and vendors to automatically provide the required data to be combined with BIM data into FM systems at minimal cost. With potentially hundreds of kinds of O&M data from building systems, transforming FM practices involves creating a seamless data exchange process and converting the process into a standard. Based on the questionnaire results, we concluded that in the most current practice, BIM data generated in form of COBie spreadsheet is not sufficient to support FM systems; manual data entry is still required to enter manually the information related to equipment manufacturing details (such as spares, warranties details, installing date, expected life, etc.). Accordingly, we proposed a conceptual framework that combines BIM data with other external data sources such as spares submittal logs and product data sheets to generate a rich database that includes all required facilities information. The proposed framework suggests to collect from different sources and then store the collected data in external database that will be used for further data manipulation to generate COBie spreadsheets that include manufacturer information extracted from product data sheets and spare parts log submittals.

6. Validating the conceptual framework
Two focus group meetings were conducted with FM practitioners working in different organizations in the UK. The 12 FM practitioners who participated in the focus group

![Figure 6. The required information that was not included in building information modelling models](image-url)
meetings included a mix of individuals working in maintenance management, healthcare FM and total FM organizations. The participants filled various roles in their departments: facility managers, project managers, directors and technicians (Table I).

The aim of the first meeting was to validate the information exchange requirements and identify information needs and sources. A list of BIM information outputs in the form of COBie spreadsheet which was generated from as-built BIM model of COBie challenge project provided online by COBie Challenge Group was distributed to participants to evaluate information exchange requirements sufficiency. Several questions related to the identification of information exchange requirements were discussed to enable interactions among multiple participants, and the findings resulted in the identification and addition of two new data sources. The first source was the industry standard, SFG20, which included maintenance schedules, and the second source was data from the manufacturers and suppliers. The meeting participants concluded that there was a need for external data sources that are not included in as-built BIM models and/or COBie data spreadsheets. Based on the results of the focus group meeting, we developed further our framework to combine different data sources extracted from the industry standards (SFG20) and from manufacturers and suppliers through a web-based interface with as-built BIM model data to provide a single comprehensive data source. Figure 7 shows the developed framework for the information exchange process between various data sources including BIM models and various FM systems.

The proposed framework consists of three major layers as detailed below:

1. **Facility information layer:** At this layer, facility data are inputted and captured at different phases and stored in as-built BIM models. The as-built BIM models include a huge amount of geometric and non-geometric data about the facility equipment and components. These data are then transferred to the external database via IFC using the IFC-to-DB module. The basis of an IFC is to generate a solo model schema supporting information exchange between different software tools. This can viewed by different members during the project lifecycle in a different way based on their information requirements. These views are known as

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Table I. BIM practitioners' background
the Model View Definition (MVD). One of these views is the FM handover view known as COBie. The recommended view in our proposed framework is the IFC2 × 3 Extended FM Handover View as shown in Figure 8.

2) Maintenance information layer: Some required data related to maintenance are not included in as-built BIM models (such as preventive maintenance tasks, frequencies and durations) and as such could not be generated automatically using COBie add-ins. At this layer, this type of data is collected from different sources, namely, the industry standards (SFG20) and the proposed user-facing web-based system. The SFG20 can be available in different formats (PDF and XML formats).

In the proposed framework, SFG20 XML as shown in Figure 9 is exported to the external databases for further data manipulation to extract preventive

Figure 8. IFC2 × 3 extended FM handover view
maintenance schedules, legislation requirements and critical assets information that are needed to support FM systems and can be included in COBie spreadsheet in job, resource, issue and document sheets.

All data collected at this layer will be stored in the same external database for further data manipulation.

In the proposed framework, we proposed a web-based graphical user interface (wGUI) to enable manufacturers, suppliers and vendors enter products data related to O&M and store these data in the external smart database as shown in Figure 10. The user selects a building type by typing its name on the window and loads the selected type. When the selected type is loaded, type specifications, manufacturer information, guarantee and warranty information get populated. The user then edits information and stores on the same external database. The addition of product information will provide the missing information that usually is ignored during the preparation of BIM as-built models and will enable to produce a rich COBie sheet that includes all required O&M information.

(3) CMMS/CAFM information layer: At this layer, a rich COBie spreadsheet is generated from the different data sources for FM using a ‘COBie-lizer’ module. Where COBie existing add-ins application have their own limitation in generating ten sheets only, COBie-lizer module has the capability of developing relationship mapping between the external database and COBie sheet schema to generate a rich COBie spreadsheet that includes all required O&M information as shown in Figure 11.

After developing the information exchange framework, we conducted the second focus group meeting to present and validate the developed framework. Participants were asked several questions to open a discussion and stimulate interactions among participants to evaluate and validate the presented framework (Table II).

In conclusion, all participants agreed that combining BIM data with other data sources such as SFG20 and manufacturers’ information will facilitate automated mobilization of
Figure 10.
Web-based user interface information requirements accessibility

Figure 11.
Data outputs included in COBie spreadsheet generated by COBie-lizer
assets registry and maintenance schedules in FM systems. Moreover, all the participants felt that the framework we developed could provide comprehensive, accurate information about the facility and its components from a single source which would improve the facilities information management practice. The only two things participants would add at this stage were a method for identifying data outputs that match FM system inputs and a way to define naming/coding systems for facility component to insure accurate data import from COBie spreadsheets into FM systems.

7. Conclusions and recommendations
FM teams depend on multiple information systems to efficiently operate and maintain buildings. Current FM systems lack interoperability capabilities, which results in poor data management. One critical measure of building operations and maintenance is data accuracy and availability; however, capturing, storing and exchanging data within a large building is cumbersome and requires standardized processes. In this research, we investigated the current methods and tools for pushing data out of BIM models into FM systems, and our data analysis confirmed the importance of having a standardized information exchange process between BIM and FM systems. The results also revealed the need for other data sources to provide data that is not included in as-built BIM models and/or COBie spreadsheets such as maintenance data. Based on these results, we proposed a framework for a seamless information exchange between various data sources including BIM models and FM systems using an open-data format to overcome interoperability problems. The proposed framework works on three different levels. At the first level, data are extracted from BIM models to the external database using the open standard schema IFC. Data are then manipulated to identify the required FM information. At the second level, the required information related to maintenance schedules is extracted from two sources:

1. the industry standards (SGF20); and
2. the proposed web-based interface that allows different stakeholders to enter maintenance data directly into the same external database.

At the third level, data from BIM models and data collected from various sources are presented as a COBie spreadsheet using the COBie-lizer module; then data are imported from the COBie spreadsheet into CAFM/CMMS software. Connecting multiple data streams into one external database provides a seamless data flow. This would guarantee comprehensive yet specific data outputs for FM systems inputs. Having a seamless data flow that collects data automatically from different sources will improve the data exchange process and reduce the time and effort needed to enter data manually into FM systems. Moreover, this will provide FM teams with the required data about building equipment and

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Table II. Demographic information about focus groups
components that will allow them to respond to various maintenance problems more efficiently. Our research findings were validated in terms of the sufficiency of the proposed framework to respond to FM information needs and to evaluate the representativeness of the identified information sources as shown in Table III. This validation was accomplished through focus group meetings in which we worked with 12 experienced FM practitioners from different FM organizations.

The outcomes of the analytical exploratory study in this research can be claimed as a knowledge contribution for the following reasons:

- The majority of the exploratory studies conducted in this area focused on examining broadly BIM implementation in FM, while the exploratory study in this research focused on exploring the current BIM state in FM with focus on information exchange process and interoperability between BIM and FM systems.
- The outcomes of this exploratory study shed the light on current challenges facing information exchange process between BIM and FM systems reported by BIM experts who used BIM to support FM in real practice.

These rich insights which were generated from participant’s experience in the same field contribute to better understanding of the current challenges facing BIM implementation in FM and verify the necessity to develop pragmatic solutions to overcome these challenges.

Furthermore, this research contributes to the body of knowledge by proposing a novel framework for seamless information exchange between BIM and FM systems. The proposed framework enables users to retrieve various data sources and transfer the collected data seamlessly into FM systems using an open data format to overcome interoperability issue. The illustrated framework shows how BIM-based facilities information management can retrieve data from BIM models using IFC file, industry

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<td>Based on what we presented today, do you think that combining BIM data, industry standards and manufactures/suppliers product data will facilitate automated mobilisation of asset registers and maintenance schedules in CAFM/CMMS?</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Based on what we presented today, do you think that combining BIM data, industry standards and manufactures/supplier products data will improve the quality and accuracy of asset information and accordingly enhance the facilities information management practice?</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>It depends on the data accuracy of BIM as-built models</td>
</tr>
<tr>
<td>Based on what we presented today, do you think that the proposed framework is sufficiently responsive to facilities management systems (CAFM/CMMS) information needs?</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Based on what we have presented today, in your opinion, what is the most important issue that you would like to highlight to enhance the proposed conceptual framework?</td>
<td></td>
<td></td>
<td></td>
<td>To identify FM systems information requirements, To define naming/coding system at early stage to facilities the information import process into FM systems</td>
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Table III. Focus group questions and discussion
standards for maintenance using SFG20XML and manufacturing data using the web-based graphical user interface and then generate a single source of digital data output to support FM systems input. The main practical advantages of the proposed system are:

- The proposed solution is capable to take advantage of the existing interoperability solutions created by the industry, namely, COBie and bridge the gap of the existing COBie add-in applications limitations by generating a rich COBie spreadsheet that includes all required FM systems input. Through this, manual data entry of O&M data could be reduced dramatically.

- Information quality could be effectively improved by managing fragmented data sources and manual data entry.

- Facilities information management practice could be efficiently improved by providing a single digital source of well-identified data output for FM systems inputs.

This could solve the issue of lack of interoperability between the various FM systems and could increase data credibility.

The next stage of this study will have to implement and demonstrate the proposed framework of information exchange between BIM and FM systems using a real case study. Another area of further research would be to develop a taxonomy of specific BIM data outputs for FM systems inputs.

References


Further reading


About the authors

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Neural network models for actual duration of Greek highway projects

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Abstract

Purpose – This paper aims to examine selected similar Greek highway projects to create artificial neural network-based models to predict their actual construction duration based on data available at the bidding stage.

Design/methodology/approach – Relevant literature review is presented that highlights similar research approaches. Thirty-seven highway projects, constructed in Greece, with similar type of available data, were examined. Considering each project’s characteristics and the actual construction duration, correlation analysis is implemented, with the aid of SPSS. Correlation analysis identified the most significant project variables toward predicting actual duration. Furthermore, the WEKA application, through its attribute selection function, highlighted the most important subset of variables. The selected variables through correlation analysis and/or WEKA and appropriate combinations of these are used as input neurons for a neural network. Fast Artificial Neural Network (FANN) Tool is used to construct neural network models in an effort to predict projects’ actual duration.

Findings – Variables that significantly correlate with actual time at completion include initial cost, initial duration, length, lanes, technical projects, bridges, tunnels, geotechnical projects, embankment, land requirement (expropriation) and tender offer. Neural networks’ models succeeded in predicting actual completion time with significant accuracy. The optimum neural network model produced a mean squared error with a value of 6.96E-06 and was based on initial cost, initial duration, length, lanes, technical projects, tender offer, embankment, existence of bridges, geotechnical projects and landfills.

Research limitations/implications – The sample size is limited to 37 projects. These are extensive highway projects with similar work packages, constructed in Greece.

Practical implications – The proposed models could early in the planning stage predict the actual project duration.

Originality/value – The originality of the current study focuses both on the methodology applied (combination of Correlation Analysis, WEKA, FannTool) and on the resulting models and their potential application for future projects.

Keywords Neural networks, Attribute selection, Highway construction, Predicting models, Project actual duration, WEKA

Paper type Research paper

1. Introduction

The uniqueness of each project according to Hodgson et al. (2011) delivers risks in the prediction of a construction project’s duration. Research suggests that project location is one of the major differences in construction of highway projects. The unique legal framework in each country influences project implementation, and project procurement systems and
contract types (Antoniou et al., 2014). Furthermore, construction projects are influenced by many parameters which alter the cost and schedule planning, both internal and external.

In addition, projects are largely dependent on geomorphology of the district (Jiang and Wu, 2007). The construction site accessibility according to Shah and Dawood (2011) and especially materials’ procurement also play a vital role in construction (Aretoulis et al., 2010). Greek construction projects are faced with a number of external parameters that could derail significantly both project duration and cost. These unforeseen events include the existence of significant and extensive archaeological findings, which create a serious pause in the project’s development. In this case, all construction activities are halted and archeological services (different per historical finding and historical era) take over the construction site in order to properly process all the findings. Such events cause cost overruns and time delays, and they could even change the design and route of the road, and sometimes even cancel the whole project. It should be emphasized that such occurrences are very often in Greece and their influence on time and cost is severe.

The next challenge focuses on environmental protection issues that each project should take care. These are time consuming matters that in many project cases altered entirely the project design. Greek terrain is extremely volatile both regarding the surface and underground conditions, and thus calls for completely different construction approaches even within the same project. This also translates into cost and time deviations. Land acquisition (expropriation) is one other critical parameter in the project implementation. In many cases, a court decision is required that takes up a lot of time. Finally, project financing is last but not the least of the problems. Due to the economic crisis, funding sources are limited and the funding terms, conditions and especially the financial cost is very significant.

It should also be noted that the available contract types currently used in Greece for the implementation of public infrastructure projects are specific and include: Unit price method and Lump sum/fixed price. Cost plus percentage fee, while allowed according to Greek law, is only employed in practice for small scale projects, while the Cost plus fixed fee is not used for Greek public work projects (Antoniou et al., 2013; Antoniou et al., 2014). Every potential contractor provides a discount on the budgeted cost. The lowest bid is the one that is awarded the project. Nowadays, due to the financial stagnation and the intense competition, the discounts offered could range between 40 and 60 per cent, leading many projects to failure. Contractors could not complete the project with such exhausting discounts.

At the same time, the procurement systems used internationally include traditional (design-tender-construction), traditional fast track, design and build, private–public partnerships, construction management, management contracts and partnering. It is worth mentioning that during the past couple decades, for the procurement of major highway projects in Greece, all of the aforementioned procurement systems have been used except for management contracts and partnering. The latter systems are not foreseen in Greek public works legislation (Antoniou et al., 2016).

The aim of this study is to highlight and evaluate parameters that correlate with the actual project duration and produce neural network models to predict a reliable final duration for highway construction projects based on data available at the bidding stage.

The current research approach also aims at considering special characteristics of projects, realized in Greece. These include archeological findings, type of terrain and land expropriation. This paper presents the results of a relevant literature review on construction project duration, and the recorded corresponding findings, with emphasis on the parameters that have been identified. Then, focusing on our projects’ sample, descriptive statistics are used to provide an overview of the projects, then correlation results of the selected variables, as well as the impact they have on the duration of highway projects are highlighted. Variable selection is further
2. Project duration prediction models

There exists a significant number of studies that focus on the estimation of highway projects’ duration. Each study focuses on various characteristics of the project and the location where the project is implemented. All research approaches are aiming at using data available at the planning stage to provide insights on the actual project duration. Al Nasseri et al. (2016) proposed and adopted a taxonomy of planning and scheduling methods, to facilitate project managers in selecting the most appropriate tool for each project. Waziri et al. (2017) developed through regression analysis highway construction duration models by incorporating relevant predictor variables, with statistically significant relationship with highway completion time. The study was based on historical data of highway projects initiated and completed between 2007 and 2012. The emphasis was on the collection of homogenous data in terms of time, cost and other economic variables. The paper proposed three multiple regression models in the form of linear, semi-log and log-log transformations which were statistically significant and had a good fit to the data.

Jiang and Wu (2007), after analyzing 1818 projects from the area of Indiana (Indiana Department of Transportation), reported that factors which affect directly the duration and the cost of each project include: type of the project, production rates of the construction firm, location of the project and weather condition. Long and Ohsato (2009) introduced a new method for scheduling repetitive construction projects with several objectives including project duration, project cost or both of them and based on genetic algorithms.

Hosseinian and Reinschmidt (2015) research was aimed at finding a best progress model for tunneling projects with the new Austrian tunneling method (NATM) by conducting Bayesian analysis on available data of a massive project. The analysis revealed that the dual Gompertz function was the most reliable model for this purpose. The results of this research bring advantages to future NATM tunnel constructions.

Moreover, Arun and Rao (2007) proposed an innovative decision support tool that could predict duration overrun, cost overrun and activities associated with any specific delay in highway construction projects. The basis for the proposed approach used simulation models as a knowledge base for generating the duration and cost overruns. Furthermore, the simulation models for duration and cost overruns of the project were focused on the nature of the delay, activities connected with the delay and stochastic nature of the duration and cost overruns.

Furthermore, Aziz et al. (2007) developed a tool, based on statistical regression analysis, which except from predicting the cost and time of a project would, also, help to evaluate the project’s performance during construction. In this study, three methods of analysis were used: ridge regression analysis, general regression analysis and non-linear partial least-square regression analysis. Data collected from completed projects included the type of pavement, contract value, duration and project miles.

Marzoughi et al. (2018) focused their research on introducing a decision support framework for estimating project duration under the influence of weather. Their study proposed a five-module framework that integrated weather variables, project performance variables and duration of project activities. Their approach implemented expert knowledge about the importance of weather variables, pairwise comparisons of weather variables with respect to different performance criteria, and similarly, pairwise comparisons of
performance variables with respect to project activities. The study moved on to produce a model, using multivariate statistical techniques and an analytical network process (ANP), to estimate the duration of project activities, taking into account the impact of weather.

El-Rayes and Kandil (2015) introduced a multi-objective optimization model that supports decision makers in transforming the traditional 2D time-cost tradeoff analysis to an advanced 3D time-cost-quality trade-off analysis. The study produced a multi-objective genetic algorithm to quantify and consider quality in construction optimization.

Moreover, Williams et al. (2009), used data from 311 projects from Virginia and Texas and followed the notion, that construction time is independent of the cost and thus they established two different models.

Glymis et al. (2017) proposed three, selected, neural network models for the prediction of actual project duration for highways, based on tender budget, length of highway project, number of lanes, number of technical projects, number of bridges, tunnels and road total length.

Liu (2011) divided the parameters in highway construction into two groups: weather conditions and the other factors. According to the different characteristics of these two groups of the random factors, the study introduced different methods to deal with them when estimating the work duration. The computer simulation technique was used to estimate the effect of weather conditions. PERT method was implemented to estimate the effect of the other random factors.

Project success modelling is the focus of the next research initiative. In this context Wang et al. (2009) used neural networks to build credible models linking pre-project planning and project success. Success was also the focus of research by Wang et al. (2012). They developed artificial neural networks ensemble and support vector machines classification models to predict project cost and schedule success. The model input data was based on early planning.

Aleithawe et al. (2011) suggested that the development of a highway construction project forward is based on the ability to acquire the right-of-way (ROW) in a timely manner. If there is a delay in the acquisition process, then major delays occur to the construction phase. Thirty-five projects, with 1,478 parcels, acquired by the Mississippi Department of Transportation (MDOT), were randomly selected for analysis. The latter identified the factors affecting acquisition duration. The data were analyzed using Statistica7. Condemnation ratio, number of revisions (design changes), and number of parcels per project were identified as factors influencing acquisition delay. A ROW acquisition regression prediction model was developed and then tested.

Tradeoff among time, cost and quality is the next research initiative. Huang et al. (2008) introduced a model of multi-attribute utility function to examine the tradeoff among time, cost and quality in construction projects. More specifically, critical path method (CPM) and ant colony algorithm based on modified selection strategy and global pheromone were implemented in order to identify the optimal decision result. Furthermore, Anastasopoulos et al. (2011) used data from 1,722 projects from Indiana and the variables which were chosen as influential, included project time delay, project cost, project type, weather, level of competition, difference between the winning bid amount and the engineer’s estimate and finally difference between the winning bid amount and the next lowest bid.

Han et al. (2013) aiming to increase accuracy of projects duration of highways during construction period, a new method was established for road duration risk, based on the risk analysis theory. The following parameters were considered: allowable stage duration, expected according to the characteristic of road construction stage duration, risk rate of stage duration, weight of stage duration and stage time risk.
Kaleem et al. (2014) focused on highway project duration estimation. The considered variables included: planned cost and project type which are known at the planning phase. Available data also considered project types such as pavement construction, improvement, rehabilitation and bridge construction projects of National Highway Authority, Pakistan. The approach produced a mathematical relationship between highway project duration, planned cost and project type.

Moreover, Hancher and Rowings (1981) proposed a method for the Indiana State Highway Commission (ISHC) which implemented some of the advantages of critical path methods, but did not require the preparation of a graphic network. The approach assigned more consistency in the determination of contract time estimates by highway personnel. The contribution of the current study included a schedule guide for the field engineers during construction.

The influence of the procurement systems on project duration is the subject of the next study. Migliaccio and Shrestha (2009) analyzed design-build (DB) procurement activities’ durations for highway projects. Results revealed that project size measured by contract dollar amount affects the duration of DB procurement activities. Procurement durations had no correlation with project cost for projects costing less than $250m. On the other hand, when the projects cost more than $250m, a linear correlation between these two variables appeared.

Pewdum et al. (2009) focused their research on the collection of highway construction project data and subsequent analysis to find out factors affecting project final budget and duration before developing the forecasting models. Their approach was based on Artificial Neural Network (ANN). The forecasting results obtained from the proposed method were compared with those obtained from models based on earned value. Research also investigated the performance of more detailed work packages. In this context, Hola and Schabowicz (2010) produced a neural network based model to predict productivity for selected sets of machines and to calculate the task execution time and cost.

Weather conditions could be a significant parameter in project implementation. Pan (2005) examined productivity and duration of highway construction activities subject to the influence of rain. The approach presents a model that uses historical daily rainfall data and experts’ knowledge and uses fuzzy set concept for assessing the impact of rain on project completion. The methodology is based on a fuzzy reasoning knowledge-based scheduling system. The introduced system can assist contractors to more reliably estimate activity durations for projects in geographical locations where rainfall data are available.

Irfan et al. (2011) investigated the estimation of highway project duration on the basis of variables which were known at the planning phase, such as planned cost, project type and contract type. The approach of the study focused on mathematical relationships among highway project duration and the magnitude of the planned cost, project type and contract type. The main findings suggested that all other factors remaining the same, the duration of fixed-date deadline contracts generally exceeded that of fixed-duration contracts. Furthermore, the paper highlighted that higher levels of planned cost translated non-linearly into greater project duration.

Antoine et al. (2018) focused on investigating the relation among project duration, project intensity and timing of cost certainty in highway project delivery methods. They concluded that alternative contracting methods are viable options for shortening project durations, establishing early cost certainty during project delivery and delivering projects at a more intense pace. More specifically, alternative contracting methods of construction manager/general contractor CM/GC and Design Build are superior to the traditional Design Bid Build method for the project performance.
It should be mentioned that the effort to model and predict project performance is a very complicated task. The parameters both project internal and external are extensive. Even micro and macro-economics are involved in the project performance. A relevant study by Okoye et al. (2018) connected construction sector and oil prices, and the actual gross domestic product (GDP).

Ford et al. (2004) examined the usefulness of constructability reviews on the reduction of project duration. Their findings revealed that there exists a connection among reviews and duration. More specifically, their study managed to model and analyze their relationship. The findings revealed how intermediate-sized constructability reviews reduced project durations and the potential impacts of a design-build approach on constructability review effectiveness.

Finally, a model developed regarding the North American region by Irfan et al. (2011), aimed to produce a user-friendly tool for estimating the duration of the project without complex variables and for this reason the examined data included project duration, project location and project type. This model would be used for managing the contract and the assessment of the tender offer. Based on the international experience, along with the uniqueness of the Greek highway projects (public infrastructure projects legislation, archeological findings, environmental permits, financing), an approach, customized especially for Greek public projects is considered essential and thus presented in the current paper.

3. Methodological approach
The current research is aimed at the production of reliable and efficient neural network models for the prediction of actual duration, with focus on the construction of highway projects, in Greece. The sample projects under examination include 37 highway projects of similar extent and content. For these specific projects it became possible to record detailed amount of the same type of data, both quantitative and qualitative. The methodology steps included the following:

Step 1: Consideration of 37 selected highway projects and collection of corresponding data.
Step 2: Construction of an appropriate SPSS database, including both quantitative and qualitative variables.
Step 3: Descriptive statistics of the sample projects’ variables.
Step 4: Correlation statistical analysis among the available variables and actual project duration. Analysis was conducted one time for quantitative variables and a second time for mixed variables, both quantitative and qualitative variables.
Step 5: Creation of a ranked list of variables, based on a decreasing degree of correlation coefficients for potential input neurons.
Step 6: Application of the “Attribute Selection” module of WEKA application for selecting subsets of variables.
Step 7: Proposal of neural network models, based on FANN tool. The models were created starting with the highest correlating variable and then adding one more variable each time from the ordered list based on correlation degree (correlation coefficient) (Step 5) and with the WEKA proposed set of variables.
Step 8: Comparison of the performance of the produced NN models.

The methodological approach is depicted in Figure 1.

3.1 Considered variables
An SPSS database was organized to record all the available variables. Variables could be characterized as quantitative and qualitative. The quantitative variables take on numerical
values, and the qualitative variables take on binary (Yes/No) or ordinal values. Table I depicts the available variables:

The explanation and type of each considered variable is as follows:

- **Project length**: The total length of the highway in meters (side road’s length is added to the length of the main road).
- **Tender offer**: The budget cost, for the project in euros, from the government (only public projects are considered).
- **Lanes**: The number of lanes per direction.
- **Initial duration**: The project’s estimated duration.
- **Technical projects**: Number of technical projects in this highway project.
- **Landfill existence**: Can only take the values of “0” and “1” (if there has been no landfill, the variable’s value is 0, in the opposite case, the variable’s value is 1).
- **Land requirement**: Can only take the values of “0” and “1” (if there has been no land requirement, the variable’s value is 0, in the opposite case, the variable’s value is 1).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Qualitative variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantitative variables</td>
<td>Qualitative variables</td>
</tr>
<tr>
<td>Continuous</td>
<td>Binary</td>
</tr>
<tr>
<td>Project length</td>
<td>Landfill</td>
</tr>
<tr>
<td>Initial cost</td>
<td>Land requirement</td>
</tr>
<tr>
<td>Tender offer</td>
<td>Embankment</td>
</tr>
<tr>
<td>Initial duration</td>
<td>Geotechnical project</td>
</tr>
<tr>
<td>Number of lanes</td>
<td>Tunnel</td>
</tr>
<tr>
<td>Number of technical projects</td>
<td>Bridge</td>
</tr>
</tbody>
</table>

Table I. Variables included in the SPSS database
• **Geotechnical project**: Can only take on the values of “0” and “1” (if there has been no geotechnical project, the variable’s value is 0, if there has been constructed at least one geotechnical project, the variable’s value is 1).

• **Bridge**: Can only take on the values of “0” and “1” (if there has been no bridges, the variable’s value is 0, if there has been constructed at least one bridge, the variable’s value is 1).

• **Tunnel**: Can only take on the values of “0” and “1” (if there has been no tunnels, the variable’s value is 0, if there has been constructed at least one tunnel, the variable’s value is 1).

• **Embankment**: Qualitative variable, the value of this variable ranges from 1 to 3, according to the height of the embankment (up to 4 m = 1, between 4 and 10 m = 2, over 10 m = 3).

### 3.2 Sample and database description

The database included data from 36 Egnatia Odos’ sub-projects and 1 smaller project in terms of acreage, cost, and time of completion, located in Greece. Egnatia Odos is one of the most modern highways in the Southeast Europe and part of the TEN-T corridors. The projects were selected on the basis of data uniformity and availability. A database was created using SPSS to proceed in the subsequent analyses. The database consists of 37 cases (number of projects) and 12 variables, which cover common available data across all the projects and according to expert opinion greatly affect the project duration. These variables were recorded as quantitative and also transformed, where possible, into qualitative ones to facilitate additional statistical analyses. Six variables remained as quantitative, while the other six were transformed into qualitative. Descriptive statistics of the sample are presented in Table II.

### 3.3 Correlation analysis for quantitative variables

The values of the IBM SPSS Statistics database were used to identify the correlations among the independent quantitative variables and actual project duration. The Fann Tool, works in a most reliable way with quantitative variables rather than qualitative. Furthermore, based on the findings of the correlation analysis, a number of neural networks were designed and implemented, to construct appropriate models for the prediction of actual project duration. According to Field (2009), Pearson correlation coefficient and the significance value, are the indicating factors for the evaluation of the correlation analysis’ results. The Pearson correlation coefficient takes on values close to 1 for strong relationships and −1 for adverse strong relationships. In addition, significance values less than 0.05 reveal strong correlation and those

<table>
<thead>
<tr>
<th>Project attributes</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Sum</th>
<th>Mean</th>
<th>Std. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>INITIAL COST (€)</td>
<td>22,57,04,803</td>
<td>10,94,800</td>
<td>22,67,99,603</td>
<td>1,97,83,86,760</td>
<td>5,34,69,912</td>
<td>95,64,893</td>
</tr>
<tr>
<td>INITIAL DURATION (days)</td>
<td>803</td>
<td>110</td>
<td>913</td>
<td>22560</td>
<td>610</td>
<td>30</td>
</tr>
<tr>
<td>LENGTH (km)</td>
<td>31,380</td>
<td>1,320</td>
<td>32,700</td>
<td>4,58,319</td>
<td>12,387</td>
<td>1,363</td>
</tr>
<tr>
<td>LANES (number)</td>
<td>6</td>
<td>2</td>
<td>8</td>
<td>193</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>TECHNICAL PROJECTS (number)</td>
<td>18</td>
<td>0</td>
<td>18</td>
<td>178</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>EMBANKMENT (number)</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>81</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>TENDER OFFER (€)</td>
<td>24,23,90,337</td>
<td>11,90,000</td>
<td>24,35,80,337</td>
<td>2,59,08,38,567</td>
<td>7,00,22,664</td>
<td>1,07,83,317</td>
</tr>
<tr>
<td>FINAL DURATION (days)</td>
<td>2034</td>
<td>218</td>
<td>2252</td>
<td>40300</td>
<td>1089</td>
<td>65</td>
</tr>
</tbody>
</table>

Table II. Sample descriptive statistics
values that fall among 0.05 and 0.06 demonstrate the tendency to correlate. Table III depicts the results with the values that met the previously mentioned criteria (only the cases where two tailed significance was below 0.05):

A brief look on the correlation analyses’ results reveals that actual project duration is associated in descending correlation degree with the following variables:

- initial cost;
- tender offer;
- initial duration;
- number of lanes; and
- length.

3.4 Correlation analysis for both quantitative and qualitative variables
In this case, qualitative variables were also included as they are presented in Table IV.

The ranked order based on correlation coefficients is the following:

- initial cost;
- tender offer;
- initial duration;
- embankment;
- number of lanes;
- existence of geotechnical projects;
- length;
- existence of bridges; and
- existence of tunnels.

4. Application of neural networks
FANN Tool application was implemented to produce the neural network. It should be mentioned that the FANN library (FANN) is a free open source neural network library. The specific library

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variables</th>
<th>Initial duration</th>
<th>Length</th>
<th>No. of lanes</th>
<th>Tender offer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual project duration</td>
<td>0.678**</td>
<td>0.670**</td>
<td>0.413*</td>
<td>0.465*</td>
<td>0.678**</td>
</tr>
</tbody>
</table>

Notes: N = 37, not significant (p > 0.05), *p < 0.05, **p < 0.01, ***p < 0.001, two-tailed significance

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variables</th>
<th>Initial</th>
<th>Bridge-</th>
<th>Tunnels</th>
<th>Geotechnical project</th>
<th>Tender offer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual project duration</td>
<td>0.465*</td>
<td>0.678**</td>
<td>0.670**</td>
<td>0.413*</td>
<td>0.370*</td>
<td>0.341*</td>
</tr>
</tbody>
</table>

Notes: N = 37, not significant (p > 0.05), *p < 0.05, **p < 0.01, ***p < 0.001, two-tailed significance
implements multilayer artificial neural networks in C and provides support for both fully and sparsely connected networks. Furthermore, it includes a framework for easy handling of training data sets. It is indeed an easy to learn and use application and at the same time versatile, well-documented, efficient and fast. In essence, FANNTool is a Graphical User Interface (GUI) to the FANN library. Finally, it facilitates easy usage without the need of programming. Summarizing, this specific tool facilitates a number of relevant processes (FANN Tool Users Guide, 2018):

- preparation of the data in FANN library standard;
- design of an ANN;
- training of the designed ANN;
- testing of the trained ANN; and
- applying of the trained ANN.

One of the following learning algorithms can be selected: FANN Train Incremental (gradually increasing), FANN Train Batch (clustering), FANN Train Rprop (Resilient backpropagation) and FANN Train Quickprop (Glymis et al., 2017).

The basic functions of the software include:

- Neural NEtwork → Detect → Optimum training algorithm: Each possible training algorithm is used for several epochs. All other parameters are fixed and the weight initialization is identical. The training algorithm showing the lowest MSE is picked (FANN Tool Users Guide, 2018).
- Neural network → Detect → Optimum activation functions: Each possible activation function is used for several epochs. All other parameters are fixed and the weight initialization is identical. The activation function yielding the lowest MSE is picked (FANN Tool Users Guide, 2018).
- Neural network → Train → Normal: Fixed topology training. The size and topology of the ANN is determined in advance and the training alters the weights to minimize the difference between the desired output values and the actual output values (FANN Tool Users Guide, 2018).
- Neural network → Train → Cascade: Evolving topology training. The training starts with an empty ANN, only consisting of input and output neurons. Hidden neurons and connections are added during training, to reach the same goal as for fixed topology training (FANN Tool Users Guide, 2018).

Neural networks produced a number of models. The dependent variable was “Actual Project Duration” in days. Twenty-one projects were used for training the neural network and sixteen projects were used for testing the produced neural network. The methodology involving the application of neural networks for the prediction of actual duration is based on multiple neural networks designed and applied specifically for the problem at hand.

The current research is contributing and focusing on identifying the best possible combination of input variables for the optimum prediction. Regarding the structure of the neural network and the relevant equations, these are left to the application itself to search and identify in order to define the optimum design and parameters each time.

### 4.1 Neural network models based on quantitative and qualitative variables

The pool of available variables for neural network construction for actual project duration prediction is depicted in Table III. Neural network models are presented in the following Table V, along with the input variables and the minimum squared error (MSE). The models
are ranked in increasing order of MSE value. The first model to be implemented used as a single input neuron the top correlated variable. Then each consecutive model was realized by adding each time a new, additional, variable. The addition of new variables was following the correlation coefficient based order. Only the third model is an experimental trial based on testing, that resulted in equal performance with the second in order model. The resulting models are depicted in Table V.

The best performing model is the one that includes the top 12 variables (Model 1), namely, initial cost, initial duration, length, lanes, technical projects, bridges, tunnels, geotechnical projects, embankment, landfill, land requirement and tender offer. This neural network model has a MSE equal to 1.53E-06.

4.2 Neural network models based on quantitative and binary definition of qualitative variables

In this case, each qualitative variable breaks into two individual variables the corresponding TRUE that receives value 1 when the assumption is true or value 0 if the assumption is false, and the corresponding FALSE that receives value 1 when the false assumption is true or 0 if it is incorrect. Neural Network models are presented in Table VI, along with the input variables and the minimum squared error (MSE).

The best performing model, of this case study, includes the top 12 variables (Model 2) based on their correlation ranking, namely, initial cost, initial duration, length, lanes, bridges-TRUE, bridges-false, tunnels-TRUE, tunnels-FALSE, geotechnical projects-TRUE, geotechnical projects-FALSE, height of prani and tender offer. This model has MSE equal to 2.54E-06. Another model that has small MSE (equal to 7.41E-06) is the model (Model 1) which includes 17 variables, namely, initial cost, initial duration, length, lanes, technical projects, bridges-TRUE, bridges-FALSE, tunnels-TRUE, tunnels-FALSE, geotechnical projects-TRUE, geotechnical projects-FALSE, embankment, landfill-TRUE, landfill-FALSE, land requirement-TRUE, land requirement-FALSE, tender offer.

### Table V. Neural network models based on quantitative and qualitative variables

<table>
<thead>
<tr>
<th>Model</th>
<th>Name of model</th>
<th>No. of variables</th>
<th>Input variables</th>
<th>MSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial-all</td>
<td>12</td>
<td>Initial cost, Initial duration, Length, Lanes, Technical projects, Bridges, Tunnels, Geotechnical projects, Embankment, Landfill, Land requirement, Tender Offer</td>
<td>1.53E-06</td>
</tr>
<tr>
<td>2</td>
<td>Initial-9</td>
<td>9</td>
<td>Initial cost, Initial duration, Length, Lanes, Bridges, Tunnels, Geotechnical projects, Embankment, Tender Offer</td>
<td>1.50E-06</td>
</tr>
<tr>
<td>3</td>
<td>Initial-8</td>
<td>8</td>
<td>Initial cost, Initial duration, Length, Lanes, Bridges, Geotechnical projects, Embankment, Tender Offer</td>
<td>5.30E-06</td>
</tr>
<tr>
<td>4</td>
<td>Initial-7</td>
<td>7</td>
<td>Initial cost, Initial duration, Length, Lanes, Geotechnical projects, Embankment, Tender Offer</td>
<td>3.61E-06</td>
</tr>
<tr>
<td>6</td>
<td>Initial-6</td>
<td>6</td>
<td>Initial cost, Initial duration, Lanes, Geotechnical projects, Embankment, Tender Offer</td>
<td>1.65E-05</td>
</tr>
<tr>
<td>7</td>
<td>Initial-5</td>
<td>5</td>
<td>Initial cost, Initial duration, Lanes, Embankment, Tender Offer</td>
<td>2.05E-06</td>
</tr>
<tr>
<td>8</td>
<td>Initial-4</td>
<td>4</td>
<td>Initial cost, Initial duration, Embankment, Tender Offer</td>
<td>2.38E-06</td>
</tr>
<tr>
<td>Model</td>
<td>Name of model</td>
<td>No. of variables</td>
<td>Input variables</td>
<td>MSE</td>
</tr>
<tr>
<td>-------</td>
<td>---------------</td>
<td>-----------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>1</td>
<td>Revised-all</td>
<td>17</td>
<td>Initial cost, Initial duration, Length, Lanes, Technical projects, Bridges-TRUE, Bridges-FALSE, Tunnels-TRUE, Tunnels-FALSE, Geotechnical projects-TRUE, Geotechnical projects-FALSE, Embankment, Landfill-TRUE, Landfill-FALSE, Land requirement-TRUE, Land requirement-FALSE, Tender Offer</td>
<td>7.41E-06</td>
</tr>
<tr>
<td>2</td>
<td>Revised-top12</td>
<td>12</td>
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<td>2.54E-06</td>
</tr>
<tr>
<td>3</td>
<td>Revised-top10</td>
<td>10</td>
<td>Initial cost, Initial duration, Length, Lanes, Bridges-TRUE, Bridges-FALSE, Geotechnical projects-TRUE, Geotechnical projects-FALSE, Embankment, Tender Offer</td>
<td>52.6E-06</td>
</tr>
<tr>
<td>4</td>
<td>Revised-top10T</td>
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<td>Initial cost, Initial duration, Length, Lanes, Bridges-TRUE, Bridges-FALSE, Tunnels-TRUE, Geotechnical projects-TRUE, Geotechnical projects-FALSE, Embankment, Tender Offer</td>
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</tr>
<tr>
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</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>9</td>
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<td>770E-06</td>
</tr>
<tr>
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<td>109E-06</td>
</tr>
<tr>
<td>11</td>
<td>Revised-top9</td>
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<tr>
<td>12</td>
<td>Revised-top7</td>
<td>7</td>
<td>Initial cost, Initial duration, Lanes, Bridges-FALSE, Tunnels-FALSE, Height of prani, Tender Offer</td>
<td>2268E-06</td>
</tr>
<tr>
<td>13</td>
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</tr>
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<td>722E-06</td>
</tr>
</tbody>
</table>
5. **WEKA application**

WEKA is a collection of machine learning algorithms for data mining tasks. WEKA contains tools for data pre-processing, classification, regression, clustering, association rules and visualization. It is also well-suited for developing new machine learning schemes. In essence, WEKA is a machine learning software in Java. A research team in Waikato University, in New Zealand, has incorporated several standard machine learning (ML) techniques into a software “workbench” called WEKA. The name WEKA stands for Waikato Environment for Knowledge Analysis. It is an extremely efficient tool that enables a specialist in a particular field to use ML to derive useful knowledge from databases that are far too large to be analyzed by hand. The users of WEKA include ML researchers and industrial scientists. Teaching is also a field where WEKA has been widely acknowledged (WEKA, 2018).

5.1 **Attribute selection of variables**

The WEKA application was used to identify subgroups of critical variables with the chosen evaluator of “CfsSubsetEval-P1-E1”. Using the search method “BestFirst-D1-N5”, the attributes, five in number, that were considered, included initial cost, length, lanes, bridges-TRUE, tender offer. Using the search method “GreedyStepwise”, the attributes, 13 in number, that were considered, included initial cost, initial duration, length, lanes, technical projects, bridges-TRUE, bridges-FALSE, height of prani, geotechnical project-TRUE, geotechnical project-FALSE, landfill-TRUE, landfill-FALSE, tender offer.

5.2 **Neural network models based to WEKA application**

Neural network models are presented in Table VII, along with the input variables and the minimum squared error (MSE).

The best performing model includes the 13 variables selected though the search method “GreedyStepwise” of the WEKA application, namely, initial cost, initial duration, length, lanes, technical projects, bridges-TRUE, bridges-FALSE, embankment, geotechnical project-TRUE, geotechnical project-FALSE, landfill-TRUE, landfill-FALSE, tender offer. This model has MSE equal to 6.96E-06.

6. **Conclusions – further research**

The current study identified through correlation analysis using SPSS and through the WEKA application, the factors affecting the actual project duration at completion. Thirty-seven highway projects, constructed in Greece, with similar type of available data, were examined. The database consists of 12 variables which cover common available data across all the projects, such as initial cost, initial duration, length, lanes, technical projects, bridges, tunnels, geotechnical projects, embankment, landfill, land requirement and tender offer. Furthermore, a

<table>
<thead>
<tr>
<th>Model</th>
<th>Name of model</th>
<th>No. of variables</th>
<th>Input variables</th>
<th>MSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WEKA-BF</td>
<td>5</td>
<td>Initial cost, Length, Lanes, Bridges-TRUE, Tender Offer</td>
<td>1806E-06</td>
</tr>
<tr>
<td>2</td>
<td>WEKA-GS</td>
<td>13</td>
<td>Initial cost, Initial Duration, Length, Lanes, Technical projects, Bridges-TRUE, Bridges-FALSE, Embankment, Geotechnical project-TRUE, Geotechnical project-FALSE, Landfill-TRUE, Landfill-FALSE, Tender Offer</td>
<td>6.96E-06</td>
</tr>
</tbody>
</table>
A number of neural network-based models were proposed to predict the final project duration based on initial data available at the bidding stage. These findings are valuable for both the awarding authority and the contractors that undertake highway projects. The value of the research results is applicable and useful at the planning stage, tender offer and finally during construction to facilitate control and plan for the project financing.

It should be emphasized that there exist additional parameters that apply pressure on the initial project budget. These parameters are not easily evaluated and quantified. Archaeological findings, along with project financing, weather conditions, land expropriation and environmental permits are just a few causes for serious increases in the planned project duration and cost.

Considering the proposed approach, it should be mentioned that the specific methodology has advantages in comparison to other relevant models. The current methodology uses non-linear and non-parametric tools to create models for the prediction of final duration of the project. These tools are significantly more effective and reliable in comparison to linear-based approaches. Furthermore, a comparison with similar models based on neural networks will prove that the proposed approach is more reliable and potentially provides more accurate results. The reason is mainly due to the screening of input data. In the proposed approach a two-stage screening is implemented to optimize the implementation of artificial neural networks, by selecting the most “predictive” input data. In the first stage, input variables are selected based on correlation analysis. Only the most correlated variables are incrementally inserted in the model. The second stage screening includes the application of WEKA aiming at selecting the most effective sub-group of variables for incorporation in the artificial neural network. These two stages increase the reliability and accuracy of the final models. At the same time, quantitative and qualitative data have been considered. Furthermore, it becomes evident that the use of the whole set of available data do not lead to better performing models. Instead, more carefully selected input variables produce models that are more accurate. This finding saves both time and effort to collect data and at the same time decreases the calculation effort.

Nowadays, the technological development, combined with high managerial experience in contemporary and complex projects, enable the successful planning of a new project at its early stages with high accuracy. By this neural network approach, the actual duration could be predicted using customized models based on historical data and data available at the bidding stage. The main purpose is to provide to the user the ability to easily examine and investigate the new project’s duration by a simple model and with the insertion of variables’ values that are known before the initiation of the project construction. Each contractor could implement the neural network to their company’s project historical data and produce customized models for cost prediction.

The key factor for the further development of the existing models is to continuously expand the available database. The greater the sample, the higher the reliability the models will have. Moreover, correlation analysis based on qualitative data highlighted a number of additional variables. Equally important would be to include more variables in the analysis such as the diverse weather conditions and productivity rates for subcontractors, equipment and managerial staff. The results of these methods could be compared to each other and useful conclusions could emerge.

The models for the actual duration at completion, as mentioned earlier, could be used either by the awarding authority (the government in this case), or by the construction company, to realize if the proposed duration is realistic, and make educated and justified considerations on the proposed discount. Finally, regarding the actual duration at completion, the two models with the lowest MSE and based on SPSS or WEKA application are correspondingly the following:
Variables selected by SPSS (MSE = 1.53E-06)
Initial cost, initial duration, length, lanes, technical projects, bridges, tunnels, geotechnical projects, embankment, landfill, land requirement, tender offer.

Variables selected by WEKA (MSE = 6.9610^-6)
Initial cost, initial duration, length, lanes, technical projects, bridges-TRUE, bridges-FALSE, embankment, geotechnical project-TRUE, geotechnical project-FALSE, landfill-TRUE, landfill-FALSE, tender offer.

The best model is the one with the variables selected by SPSS as it provides the lowest MSE. The common variables among the two models include initial cost, initial duration, length, lanes, bridges, geotechnical projects, embankment, tender offer and landfill. The fewer the number of required variables, the easier to record or collect the necessary data and the simpler the model to implement. Each variable/parameter is unique and the way that environment affects/influences all these parameters is different. Therefore, each parameter is more or less vulnerable to external events. Taking this fact into consideration the predicting variables could be ranked or evaluated based on their vulnerability, or risk associated with each variable. Therefore, the vulnerability of each produced model could also be assessed based on a measurement of the vulnerability of each included variable. The best performing model does not make use of the “special” attributes, such as geomorphology and archeological findings.

A further research in this area could aim at the development and the comparison of the results with other methods and tools. A very interesting comparison would be with the relative results being produced by algorithmic models. Also, a wider number of projects should be included, so that correlations and trends that are not observed by this research could be identified in a more extensive research and at the same time increase models' reliability and accuracy. Moreover a better analysis would occur if additional variables were inserted like the weather conditions which is also suggested by Arditi and Bentotage (1996), Jiang and Wu (2007) or the company’s efficiency rates Arditi et al. (1996), Shah and Dawood (2011). These variables appeared frequently in the literature and seem to affect significantly the dependent variables. Unfortunately, especially for completed projects there exist no record of these data.

Finally, it is important to mention that all trials to produce neural network models, relied on the application itself to select and construct the optimum neural network “structure.” It was defined that the cascade method would be used to design the neural network. There exist fields for experimentation from the users' end, to propose their own network design, which might even lead to better performing models.

References


Further reading


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Key risk factors affecting renewable energy independent power producer (IPP) set-up projects in developing countries

The case of Ghana

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Abstract

Purpose – Sustained access to efficient electricity plays an essential role in improving living conditions of people and contributes to the economic development of the nation as a whole. Volta River Authority (VRA) mainly manages the generation plants (hydropower sources and thermal plants) alongside independent power producers (IPPs). Power generation in the country has been influenced by myriads of factors. Thus, the purpose of this study is to assess the key risk factors affecting renewable energy of IPPs set-up project in Ghana.

Design/methodology/approach – Quantitative approach was adopted for the study. Empirical investigation was carried out using the survey approach. The likelihood of occurrence of the risk and the degree of impact of same motivated the use of risk significance index to analyze the data and make deductions from the results.

Findings – From the study, three key risk factors have high level of severity, which include long and complex procedures for authorization of project activities, stability of the policy environment and ease of obtaining rights to land. These risks could be found in the business/strategic risks and policy/regulatory risks categories, respectively. A total of 25 key risk factors had moderate level of severity and 12 key risk factors have low level of severity on renewable energy IPP set up projects.

Practical implications – Top-ranked risk factors require maximum attention. The identified risks should be alleviated with strategies to reduce levels of severity by targeting either the likelihood of occurrence or the level of impact. This will serve as a catalyze to promoting renewable energy IPP set up projects in Ghana.

Originality/value – Key contribution of the paper to the body of knowledge is demonstrated by the empirical evidence of the risks IPPs are likely to encounter in setting up renewable energy plants in Ghana. The distinctive attribute of this study is further demonstrated by the fact that it focused on the set-up stage, which is a critical stage in the renewable energy provision value chain.

Keywords Ghana, Renewable energy, Risk identification, Independent power producers

Paper type Research paper

Introduction

The availability and accessibility of reliable energy is a key component in the development value chain as businesses and industries depend highly on access to energy services to function effectively (Energy Commission, 2012). The total installed generation capacity of Ghana is approximately 3,200 MW (Ofei, 2016). Out of this, 1,580 MW representing 49.9 percent is produced from hydropower sources (hydro plants of capacity more than 100 MW are
not considered as renewable energy (GOG, 2011), 1,579 MW representing 49.8 per cent is from thermal plants and 8.2 MW representing 0.3 per cent is produced from renewable energy sources (Ofei, 2016). Volta River Authority (VRA) runs 83 per cent of the generation plants while the remaining 17 per cent is managed by independent power producers (IPPs) (Ofei, 2016).

Power generation in Ghana has been greatly influenced by rainfall conditions, inflation of fuel prices, interruptions and delays in construction of new plants. Given the large dependency on hydro and thermal power plants (99.7 per cent of installed capacity), changes in weather and constraints in fuel supply severely affect electricity generation (Energy Commission of Ghana, 2017). The entire electricity demand of the country in 2015 was between 14,000 and 16,400 GWh while the available supply was around 15,000 GWh. Thus, demand exceeded supply and this affected power supply. Consequently, the country experienced intermittent supply of power leading to excessive load shedding popularly referred to locally as “dumsor” (literally referring to the rapid rate at which the power supply is interrupted). The deficit of power supply to the country was estimated at 229 GWh of electricity in October 2016 (Electricity Market Oversight Panel 'Secretariat, 2016). The nation’s energy consumption is forecasted to reach 24,000 GWh by 2020 (Energy Commission of Ghana, 2015). It is against this backdrop that a policy target was set to increase the portion of renewable energy in the generation mix from 0.3 to 10 per cent by 2020 (Energy Commission, 2006).

The availability of electrical power is an indispensable resource for the improvement of the economic fortunes of every nation. Undeniably, the unavailability of this critical resources has threatened the growth of organizations in countries where generation shortfalls have been experienced. To this end, concerted efforts has been made by countries to ensure this resource is reliably available over a significant period of time. As a result, access to electricity has featured significantly in the development agenda of nations and Ghana is no exception. Ghana has committed to provide universal access to electricity by 2020. Significantly within this universal access provision is to ensure that renewable energy constitutes about 20 per cent. Ghana is currently enjoying relative stable power supply but is occasionally plagued with challenges leading to load shedding. The key among these challenges is the lack of adequate generation capacity to match peak demands due to shortfalls in fuel supply as a result of accumulated debt owed the suppliers. For instance, it was estimated that an amount of US$900m was required to procure fuel for grid or public electricity generation in 2018. However, lack of adequate funds and high indebtedness to fuel suppliers remain a critical challenge. This problem poses a significant threat to the nation’s ability not only to enjoy reliable power supply but also provide a fertile ground to encourage investment into renewable energy. This study, therefore, leads the way by bringing to the fore the risks to anticipate in the drive to obtaining maximum investment in the renewable energy supply space.

The Government of Ghana in recognition of the role private sector plays in expanding the electricity generation market (Energy Commission, 2006), passed the Renewable Energy Act (Act 832) in 2011. By this legislative instrument, the renewable energy sector would be made attractive to investors. The Renewable Energy Act will provide fiscal incentives and a regulatory framework to regulate the sector. The provisions of the renewable energy law comprises the feed-in tariffs and renewable energy purchase obligations, which are provided to encourage investor participation in the setting up of renewable energy plants (International Renewable Energy Agency, 2015).

Ghana has set a policy target to increase the share of renewable energy in the electricity generation mix to 10 per cent by 2020 (Energy Commission, 2006). However, the
unsustainable level of the country’s public debt (70 per cent of GDP) has rendered this target difficult for government alone to reach (Ameyaw and Alfen, 2017). Thus, the Renewable Energy Act was established to regulate the sector and make it conducive and attractive for investors. As a result, institutions seeking to benefit from the renewable energy policies and incentives have initiated the process of setting up renewable energy plants in Ghana. Available data shows that the Energy Commission (EC) issued provisional licenses (wholesale electricity supply license) to 98 companies to start the process of establishing various types of renewable power plants in Ghana (Energy Commission of Ghana, 2015). However, large scale projects are the subject of excessive risks requiring identification (Ameyaw and Chan, 2015). Risk management experts say that by finding and examining threats to success, responses can easily be taken to reduce the probability of failure of projects (Schmidt et al., 2004). It is, therefore, necessary to study the risk factors of these renewable energy projects to present an authoritative risk factor list, which can be adopted by the institutions to assist them reduce the impact of those risks, should they occur on the projects. This study also, beyond the identification of the risk factors, determined their likelihood of occurrence and their respective impacts.

**Previous studies**

Several studies have identified and assessed risk factors of renewable energy projects. Mosannenzadeh et al. (2017) developed a systematic classification and analysis of the barriers hindering successful implementation of smart energy projects. Another study by Gatzert and Kosub (2015) realized that policy and regulatory risks are the major barriers for renewable energy investments. The authors suggested that besides insurance, diversification is one of the important tools for risk mitigation. Jankauskas et al. (2014) identified and assessed risks factors of renewable energy investment projects from the perspective of stakeholders. Three major stakeholders were considered, which were the public sector (the state), the funders and the investors. The top three critical risk factors according to the stakeholders are delay in the subsidy policy that affects business profitability, changes in the public opinion and lobbying of stakeholders. A study into the existing risk element of renewable energy projects by Angelopoulos et al. (2017) concluded that policy design risks represents the risk element with the greatest impact on the cost of capital. Liu and Zeng (2017) also found out from their research that policy risk was the main factor affecting the investment of renewable energy projects in the early development stages of the projects whiles market risks become the main threat when the project reach the mature development stage. Policy and regulatory risks seem to be the most consistent across multiple research studies.

Policy risks arise as a result of the application and the enforcement of regulations at the economy and project levels (Gatzert and Kosub, 2017). They are associated with the laws and regulations that possess the potential to impact the productivity, profitability and performance of the firm (Ameyaw and Alfen, 2017). These risks, according to Bond and Carter (1995), are inevitably present facing private investors and that there is limited scope for avoidance, except the inclusion of some buyout mechanisms in special circumstances. For instance, the state can insulate private investors by bearing some of the costs that may accrue as a result of government’s adverse action. Examples include length of the power purchase agreement (PPA), ease of obtaining rights to land and coordination between all government-related agencies (Holburn, 2012).

Mosannenzadeh et al. (2017) identified market risks as threats that can affect project success due to condition of the electricity market. Such risks represent the demand or price for a service, which could vary from forecast levels resulting in shortfalls in anticipated
revenue. They further averred that split incentives, demand fluctuation, drop of prices in the energy market and risk of bankruptcy during the contract period are all examples of market risks.

Ameyaw and Alfen (2017) argued out the impact of financial risk and the propensity of impacting power generation projects negatively. Financial risks comprise of risk factors relating to project financing of renewable energy IPP projects. They can arise for reasons such as price and costs increase, increase in interest rates or from a poor financial structure (Ng and Loosemore, 2007). These risks are highly inevitable because the project coordinators have no direct influence in their occurrence (Mosannenzadeh et al., 2017).

Mosannenzadeh et al. (2017) cited risks such as unavailability of proven and tested solutions, deficient planning, lack of skilled and trained personnel, lack of defined processes, etc., as technical risk. Technical risk refers to the availability of local knowledge and expertise to set-up and operate renewable energy plants. These risks are noted to occur during the entire lifecycle of the project, but particularly prone during the construction, operation and decommissioning phases (Noothout et al., 2016).

Other risk associated with renewable included but are not limited to administrative risks, environmental risks, transport/construction/completion risk and business risk. Prior to the set-up and operation of renewable energy plants, several permits are required of investors. The time required to get these documentations can prove to be daunting, potentially delaying the scheduled set-up and operation times. For renewable energy projects, these risks referred to as administrative risk occur during the planning phase of the project, where authorizing permits are required.

Environmental risks on the other hand occur due to the threats posed by the project on its environment. These risks have the potential to impact the environment by causing physical damage to the environment during the set-up and operation of energy projects with associated costs of restoration and re-habitation. These risks include negative effects of project intervention on the natural environment, inadequate or insufficient site information (soil test and survey report); and serious pollution (noise, sound and dust) caused by construction. transport/construction/completion risks comprise of risk factors relating to the construction phase of the renewable energy IPP projects. These risks constitute risks that eventuate during the construction phase capable of running the IPP project into cost and time overruns or leading to performance shortfalls of the completed project. Strategic and business risks comprise of risk factors relating to the organizational processes and procedures associated with the renewable energy IPP projects. It should be noted that, a plethora of risks are faced in setting up renewable energy set up projects, though most are characteristic of what has been described above.

Most of these studies were carried out in Europe and China where renewable energy technologies are more advanced. Again, most of these studies focused on partnerships between the private sector and the public sector public private partnership energy projects with little attention on IPPs. Also, risk factors are biased by a country’s political and economic environment, technological strength and the country’s perception of risk and risk management capability (Ameyaw and Chan, 2015). This suggests that application of these factor lists may not work in Ghana. Therefore, presenting a list of risks of renewable energy project from a different culture and geographical region will contribute to filling this research gap by widening readers’ perspective. It will further enable comparison with risks from different cultural backgrounds. Furthermore, recent studies conducted in Ghana in the renewable energy sub-sector paid little attention to the risks facing IPPs. For instance, a report produced
by Essel (2015) for a project sanctioned by the United Nations Development Program (UNDP) and the EC of Ghana reviewed past Ghanaian and Chinese renewable energy policies and strategies, essentially focusing on the identification of policy gaps and professing solutions for the Ghanaian renewable energy sub-sector (Essel, 2015). Even though the work of Bensah et al. (2015) – another project implemented by the UNDP and the EC of Ghana – focused on the private sector’s participation in the provision of renewable energy, the major aim of the study was toward the creation of an enabling environment for renewable energy technology transfer (RETT) by examining the Ghanaian renewable energy legal framework and identifying the barriers to RETT to Ghana. The lack of focus of the aforementioned studies on the risks IPPs face in setting up renewable energy projects in Ghana provides further impetus on the need for this study.

**Power generation and distribution in Ghana**

The power value chain in Ghana consists of seven institutions playing different roles aimed at ensuring that power is generated and distributed to the end users being individual homes, factories, businesses, etc. These institutions include the Ministry of Energy (MOE), EC, Public Utilities Regulatory Commission (PURC), VRA, Ghana Grid Company (GridCo), Power Distribution Services Ghana (PDS) (formerly Electricity Company of Ghana – ECG), and the Northern Electricity Department Company (NEDCo) (Figure 1). The others include the energy foundation, which is a private-public partnership initiative aimed at promoting energy conservation and the IPPs. Table I provides a brief description of their respective roles. The generation and distribution pattern relative to the various institutions are shown in Figure 1.

In Ghana, electricity generation is mainly from hydro (above 100 MW) and thermal sources. The renewable energy sources in the electricity mix are negligible, compared to the magnitude of hydropower and thermal. The total installed generation capacity is 3,200 MW, which comprises of 1,580 MW from hydro sources, 1,579 MW from thermal sources. Renewable sources are only 8.2 MW (Ofei, 2016).

**Research methodology**

This study was based on a review of literature to identify the risks affecting renewable energy projects. The respondents for the study were IPPs licensed by the EC to build and operate renewable energy plants in Ghana. The EC in Ghana is the institution in the power generation and transmission value chain mandated by law to regulate the power sector by, *inter alia*, granting licenses for players interested in the transmission, wholesale, supply, distribution and sale of electricity. There are currently 98 of these licensed companies of

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**Figure 1.**
Ghana’s power sector

Source: Electricity Company of Ghana (2017)
which 67 are setting up solar plants, 12 wastes-to-energy plants, 11 wind plants, 5 hydro plants, 2 biomass plants and 1 wave energy plant (Energy Commission of Ghana, 2015). Because of the manageable size of the population, a census survey was conducted (Turner, 2003). The respondents met two key criteria of:

1. having worked and gained experience in the Ghanaian energy sector; and
2. having duly been licensed by the EC of Ghana and have set up or setting up a plant for operation.

Field data was gathered from the IPPs registered and licensed by the EC of Ghana through a survey. A pretesting of the questionnaire was conducted by presenting a list of risk factors (50) to experts in the renewable energy sector at the EC to confirm the key risk factors encountered on renewable energy projects. Through this exercise, a total of 40 key risk factors were confirmed and these were included in the questionnaire for administration. These risks were grouped into six categories of strategic/business risks, transport/construction/completion risks, policy/regulatory risks, market risk, financial risks and environmental risks. The risk factors included in the study was based on the risk registers proposed by Zou et al. (2012), Holburn (2012), Jankauskas et al. (2014), Gatzert and Kosub (2015), Mosannenzadeh et al. (2017) and Ameyaw and Alfen (2017). The questionnaire was divided into two sections. The first section requested for demographic information of respondents. The second section contained the identified risks categories with their respective latent risk variables under each category and a two-dimensional five-point scale. The scale was used to review and indicate risks based on their probability of occurrence ($\alpha$) and levels of impact on project objectives ($\beta$) (Zou et al., 2012).

The method developed by Shen et al. (2001) in determining the risk significance index is adopted for this research due to its ability to provide a relative significance of the risk factors to enable risk ranking. Further, this method allows for averaging the scores from all respondents to obtain the average significance score for each risk (Zou et al., 2012; Shen et al., 2001). They considered the significance of risk as a function of two attributes, namely: the likelihood of occurrence of the risk ($\alpha$); and the degree of impact the risk ($\beta$). Consequently, risk significance ($RS$), is described in terms of the two attributes:

<table>
<thead>
<tr>
<th>Institution</th>
<th>Responsibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ministry of energy</td>
<td>The responsible ministry of government responsible for formulating energy policies</td>
</tr>
<tr>
<td>Energy commission</td>
<td>Energy policy advisory, planning, technical regulation and monitoring</td>
</tr>
<tr>
<td>PURC</td>
<td>Electricity tariff determination and regulation</td>
</tr>
<tr>
<td>VRA</td>
<td>Electricity generation</td>
</tr>
<tr>
<td>GridCo</td>
<td>Electricity transmission</td>
</tr>
<tr>
<td>PDS – (formerly Electricity Company of Ghana)</td>
<td>Electricity distribution (Southern sector)</td>
</tr>
<tr>
<td>NEDCo*</td>
<td>Electricity distribution (Northern sector)</td>
</tr>
<tr>
<td>Energy foundation</td>
<td>Promotion of energy efficiency and conservation</td>
</tr>
<tr>
<td>IPPs</td>
<td>Electricity generation</td>
</tr>
</tbody>
</table>

Note: *A subsidiary of VRA

Table I. Ghana’s power sector players and responsibilities
To ascertain the relative significance among the risk factors, Shen et al. (2001) argued the need to establish a risk significance index by calculating a significance score for each risk. The significance score for each risk is, therefore, calculated by multiplying the likelihood of occurrence ($a$) by the degree of impact ($b$). The significance score of a risk factor is, thus, calculated with equation (2) as:

$$r^h_k = \alpha^h_k \times \beta^h_k$$

where $r^h_k$ = the significance score for risk $h$ rated by participant $k$; $\alpha^h_k$ = probability of occurrence of risk $h$, rated by participant $k$; and $\beta^h_k$ = degree of impact of risk $h$, rated by participant $k$ (Shen et al., 2001).

To be able to rank the risks, the risk index score ($RI$) is then calculated by averaging the significance scores ($r^h_k$) from the respondents. The risk index score ($RI$) is calculated using SPSS with equation (3) (Shen et al., 2001):

$$RI = \frac{1}{n} \sum_{j=1}^{n} r^h_k$$

where $RI$ = risk index score for risk $h$; and $r^h_k$ = significance value for risk $h$ by participant $k$; and $n$ = total valid and reliable responses (Shen et al., 2001).

The matrix in Table II developed by Zou et al. (2012) from the research of Shen et al. (2001) is modified for this research. It is the representation of the conversion of the five-point scale of $\alpha$ (rare occurrence, unlikely occurrence, possible occurrence, likely to occur and highly likely occurrence) and $\beta$ (negligible impact, minor impact, moderate impact, critical impact and very critical impact) into numerical scale. The first column represents the likelihood of occurrence whiles the first row represents the level of impact of risks. The likelihood of occurrence and level of impact have five rating points each under them. For likelihood of occurrence the rating points are “rare” with a value of 0.2, “unlikely” with a value of 0.4, “possible” with a value of 0.6, “likely” with a value of 0.8 and “highly likely” with a value of 1. On the other hand, the rating points under the level of impact are negligible with a value of 0.2, minor with a value of 0.4, moderate with a value of 0.6, critical with a value of 0.8 and very critical with a value of 1. The rating points multiply each other as shown in the matrix. The ranking of the risks was based on the figures obtained with respect to the product of $\alpha$ and $\beta$.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>Negligible (0.2)</th>
<th>Minor (0.4)</th>
<th>Moderate (0.6)</th>
<th>Critical (0.8)</th>
<th>Very critical (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rare (0.2)</td>
<td>0.04</td>
<td>0.08</td>
<td>0.12</td>
<td>0.16</td>
<td>0.2</td>
</tr>
<tr>
<td>Unlikely (0.4)</td>
<td>0.08</td>
<td>0.16</td>
<td>0.24</td>
<td>0.32</td>
<td>0.4</td>
</tr>
<tr>
<td>Possible (0.6)</td>
<td>0.12</td>
<td>0.24</td>
<td>0.36</td>
<td>0.48</td>
<td>0.6</td>
</tr>
<tr>
<td>Likely (0.8)</td>
<td>0.16</td>
<td>0.32</td>
<td>0.48</td>
<td>0.64</td>
<td>0.8</td>
</tr>
<tr>
<td>Highly likely (1.0)</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>1</td>
</tr>
</tbody>
</table>
Results
A total of 98 questionnaires were distributed. All the respondents approached were managers of licensed institutions setting up renewable energy plants. In all 42 questionnaires were retrieved valid for the analysis representing 42.857 per cent response rate. Out of the 42 responses obtained, 71 per cent were setting up solar plants, 7 per cent with hydro plants, 12 per cent with waste-to-energy plants, 12 and 5 per cent with both wind and biomass plants. In respect of the experience of respondent in the renewable energy sector, 6 per cent of the respondents have been in the sector for up to 5 years, 16 per cent has been in the sector for 6-10 years, 47 per cent for 11-15 years and 31 per cent for 16-20. Overall, the respondents have adequate experience in the renewable energy sector nearing 20 years. It should be noted that the renewable energy industry is relatively young in Ghana. This shows that respondents have the necessary years of experience in the sector to effectively give rating on the likelihood of occurrence and level of impact of the key risk factors presented in the questionnaire.

The risk factors were ranked based on their risk significance indexes from the highest risk significance index to the smallest risk significance index in each category. Risk significance index is the mean significance value score for the risk factors. For the purposes of this study, the significance value was obtained as a function of the likelihood of occurrence and the level of impact of risk factor on project objectives when they occur. The risk significance index is, therefore, a reflection of the likelihood of occurrence of a risk factor and the level of impact of that risk factor on project objectives when they occur. Following the ranking, the risk factors were classified as very high, high, moderate, low and negligible based on the level of severity. Table III shows the classified risk factors and their positions.

Key risk factors
As can be seen from Table III and Figure 2 strategic/business risks and policy/regulatory risks categories were deemed to be “high”; financial risks and transport/construction/completion risks categories were deemed to “moderate”; and market risks and environmental risks were rated “low” by the respondents.

Strategic/business risks
According to Deloitte (2013), these risks are introduced as a result of the business strategy decisions and can strike quickly, relative to the other types of risks. Under strategic/business risks, there were five key risk factors presented to the respondents, namely: long and complex procedures for authorization of project activities; lack of stakeholder participation; lack of institutions/mechanisms to disseminate information; difficulty in the coordination of high number of partners and authorities; and complicated and non-comprehensive procurement procedures. The factors had risk significance indexes of 0.6800, 0.4248, 0.3771, 0.4676 and 0.4648, respectively, (Figure 3).

Long and complex procedures for authorization of project activities was ranked highest of all the risks in this category. Additionally, this risk factor was ranked as the first most critical risk among 40 risks analyzed in this study. This risk factor explains the bureaucratic nature of the processes an IPP is subjected to before receiving the approval to begin its operations. Even though Max Weber considers bureaucracy as a rational type of administration significant for the achievement of positive results, studies has found long processes in starting up business as a challenge for development in developing countries. For instance, the study of Doruk and Söylemezoglu (2014) found bureaucracy and costs as major barriers for start-ups and innovation in developing countries. This risk is further
<table>
<thead>
<tr>
<th>Risk factors</th>
<th>RI</th>
<th>Risk ranking</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategic/business risks</strong></td>
<td>0.5583</td>
<td>1st</td>
<td>High</td>
</tr>
<tr>
<td>Long and complex procedures for authorization of project activities</td>
<td>0.6800</td>
<td>1</td>
<td>High</td>
</tr>
<tr>
<td>Lack of stakeholder participation</td>
<td>0.4248</td>
<td>24</td>
<td>Moderate</td>
</tr>
<tr>
<td>Lack of institutions/mechanisms to disseminate information</td>
<td>0.3771</td>
<td>30</td>
<td>Low</td>
</tr>
<tr>
<td>Difficulty in the coordination of high number of partners and authorities</td>
<td>0.4676</td>
<td>15</td>
<td>Moderate</td>
</tr>
<tr>
<td>Complicated and non-comprehensive procurement</td>
<td>0.4648</td>
<td>16</td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>Transport/construction/completion risks</strong></td>
<td>0.4071</td>
<td>4th</td>
<td>Moderate</td>
</tr>
<tr>
<td>Very rapid technology development and related change of price for installations</td>
<td>0.5171</td>
<td>8</td>
<td>Moderate</td>
</tr>
<tr>
<td>Variations of construction programs</td>
<td>0.3524</td>
<td>33</td>
<td>Low</td>
</tr>
<tr>
<td>Unsuitable construction program planning</td>
<td>0.3371</td>
<td>35</td>
<td>Low</td>
</tr>
<tr>
<td>Unavailability of sufficient professionals and managers</td>
<td>0.3695</td>
<td>32</td>
<td>Low</td>
</tr>
<tr>
<td>Unavailability of sufficient amount of skilled labor</td>
<td>0.4152</td>
<td>26</td>
<td>Moderate</td>
</tr>
<tr>
<td>Low management competency of subcontractors</td>
<td>0.3152</td>
<td>36</td>
<td>Low</td>
</tr>
<tr>
<td>Lack of coordination between project participants</td>
<td>0.3733</td>
<td>31</td>
<td>Low</td>
</tr>
<tr>
<td>Incomplete or inaccurate cost estimate</td>
<td>0.4105</td>
<td>28</td>
<td>Moderate</td>
</tr>
<tr>
<td>Incomplete approval and other documents</td>
<td>0.4629</td>
<td>19</td>
<td>Moderate</td>
</tr>
<tr>
<td>Inadequate project scheduling</td>
<td>0.4152</td>
<td>25</td>
<td>Moderate</td>
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<tr>
<td>High performance or quality expectations</td>
<td>0.4495</td>
<td>22</td>
<td>Moderate</td>
</tr>
<tr>
<td>Excessive approval procedures in administrative government departments</td>
<td>0.4771</td>
<td>13</td>
<td>Moderate</td>
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<tr>
<td>Design variations</td>
<td>0.3981</td>
<td>29</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Policy/regulatory risks</strong></td>
<td>0.5255</td>
<td>2nd</td>
<td>High</td>
</tr>
<tr>
<td>Stability of the policy environment</td>
<td>0.6552</td>
<td>2</td>
<td>High</td>
</tr>
<tr>
<td>Difficulty in obtaining rights to land</td>
<td>0.6362</td>
<td>3</td>
<td>High</td>
</tr>
<tr>
<td>Length of the PPA</td>
<td>0.5495</td>
<td>5</td>
<td>Moderate</td>
</tr>
<tr>
<td>Coordination between all government-related agencies</td>
<td>0.5419</td>
<td>6</td>
<td>Moderate</td>
</tr>
<tr>
<td>Ease of obtaining approvals from municipalities</td>
<td>0.5143</td>
<td>9</td>
<td>Moderate</td>
</tr>
<tr>
<td>Presence of a long-term government target for Renewable energy</td>
<td>0.4867</td>
<td>12</td>
<td>Moderate</td>
</tr>
<tr>
<td>Availability of transmission capacity for the foreseeable future</td>
<td>0.4695</td>
<td>14</td>
<td>Moderate</td>
</tr>
<tr>
<td>Ease of obtaining grid connection approval</td>
<td>0.4629</td>
<td>18</td>
<td>Moderate</td>
</tr>
<tr>
<td>Transparency of the PPA bidding and award process</td>
<td>0.4133</td>
<td>27</td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>Market risks</strong></td>
<td>0.3800</td>
<td>5th</td>
<td>Low</td>
</tr>
<tr>
<td>Energy price distortion</td>
<td>0.5048</td>
<td>11</td>
<td>Moderate</td>
</tr>
<tr>
<td>Risk of bankruptcy during the contract period</td>
<td>0.4429</td>
<td>22</td>
<td>Moderate</td>
</tr>
<tr>
<td>Demand fluctuation</td>
<td>0.3381</td>
<td>34</td>
<td>Low</td>
</tr>
<tr>
<td>Split incentives</td>
<td>0.2343</td>
<td>40</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Financial risks</strong></td>
<td>0.4946</td>
<td>3rd</td>
<td>Moderate</td>
</tr>
<tr>
<td>Taxation changes</td>
<td>0.5790</td>
<td>4</td>
<td>Moderate</td>
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<tr>
<td>Availability of bank financing for the project</td>
<td>0.5171</td>
<td>7</td>
<td>Moderate</td>
</tr>
<tr>
<td>Availability of financial support for the project</td>
<td>0.5114</td>
<td>10</td>
<td>Moderate</td>
</tr>
<tr>
<td>Breaches of contracts</td>
<td>0.4648</td>
<td>17</td>
<td>Moderate</td>
</tr>
<tr>
<td>Inflation, changes in currency prices</td>
<td>0.4581</td>
<td>20</td>
<td>Moderate</td>
</tr>
<tr>
<td>Reduction of financial support</td>
<td>0.4371</td>
<td>23</td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>Environmental risks</strong></td>
<td>0.2594</td>
<td>6th</td>
<td>Low</td>
</tr>
<tr>
<td>Serious pollution (noise, sound and dust) caused by construction</td>
<td>0.2881</td>
<td>37</td>
<td>Low</td>
</tr>
<tr>
<td>Negative effects of project intervention on the natural environment</td>
<td>0.2448</td>
<td>38</td>
<td>Low</td>
</tr>
<tr>
<td>Inadequate or insufficient site information (soil test and survey report)</td>
<td>0.2352</td>
<td>39</td>
<td>Low</td>
</tr>
</tbody>
</table>

**Note:** ¹Risk significance index for a category = sum of mean of factors in each category/total number of factors in category
evidenced by the World Bank’s Ease Of Doing Business Report, which essentially measures the processes required for an entrepreneur to formally start operations including the time and cost to conclude these procedures of selected economies. The 2018 report placed Ghana in 120th position out of 190 economies considered, a drop of 12 places from 108 in 2017. Two key areas, among 11, of assessment in the World Bank’s report include dealing with construction permit and starting. These two key areas deals with the processes and
procedures, including the time and cost it takes to begin a new business. In Ghana, for an IPP to enter the electricity market, the IPP is required to undertake a pre-feasibility study and identify a buyer or an off-taker. The technical and financial viability of the project is then ascertained following the identification of the off-taker through a detailed feasibility study. The IPP then interacts with relevant authorities including EC as the licensing and technical regulator and the Public Utilities Regulatory Commission (PURC) as the pricing regulator. Site clearance is then sought from the Environmental Protection Agency (EPA) and the EC. The EPA then issues an Environmental Permit if the IPP satisfies their requirement. A Memorandum of Understanding is then signed between the IPP and the off-taker following a receipt of No-objection from the PURC. Prior to the conclusion of the PPA between the IPP and the off-taker, which essentially terminates the entire process, the IPP is required to obtain relevant approvals of identified reliefs from other authorities such as the Ghana Investment Promotion Center, the MOE and the Ministry of Finance and Economic Planning.

This procedure, even though necessary, takes a great deal of time and could impact the IPPs operations financially given the huge capital injection required to set up as an IPP and the volatile nature of Ghana’s currency against other currencies such as the US dollars. Furthermore, long and complex procedures encourages bribery and corruption, which represent a further drain on the finances of IPPs seeking to construct and operate renewable power generators in Ghana. Complex and long procedures for authorization is also noted as a disincentive for investment in renewable energies (Mosannenzadeh et al., 2017).

Policy/regulatory risk
As can be seen in Table III and Figure 4, stability of the policy environment and difficulty in obtaining rights to land were the two risk factors, among the others, that the respondents deemed to be “high” in their operations. The nature of the regulatory environment is a key factor contributing to the success or otherwise of IPPs in a country. The decision of IPPs to invest in a region or country is partly determined by the extent to which the autonomy of the regulatory authorities is protected. For instance, in low regulatory environments, where the autonomy of the regulatory agencies is maintained, making it difficult for politicians to
change their energy policies, IPPs are only focused on protecting the relationships they share with responsible regulatory agencies for policy implementation. In contrast, in high regulatory environments where the autonomy of regulatory agencies is subjected to excessive interruption of politicians, the operations of IPPs are troubled (Holburn, 2012). In Ghana, it is the sole responsibility of the PURC to set tariffs in consultation with key stakeholders based on prevailing economic conditions. However, this responsibility has sometimes being usurped by government as a result of public outcry about the cost of electricity, leading to the setting of unrealistic tariffs. Given that IPPs recoup their investment through tariffs, the unrealistic tariffs have rendered most of them to be under-recovered.

Acquisition of rights to land was also identified by respondents (IPPs) of this study as a “high” risk factor impacting their operations in this category. In Ghana, the land tenure system is described as one that is characterized by legal pluralism where there is the concurrent co-existence of customary and statutory laws, where authority to land is owned by several institutions and regulations (Djokoto and Opoku, 2010). Customary authorities (stool, skins, clans and families) predominantly own titles to land. These authorities have a total of about 78 per cent of the lands with 22 per cent owned by the state (King and Sumbo, 2015). As the vast of land is owned by individual stools, skins, clans and families, IPPs experience extreme difficulty in acquiring rights to use these lands. This is because, in some instances, there are multiple claims to the land by these people leading to land disputes. In other words, the IPPs are initially confronted with the challenge of identifying the legitimate owner of the land, potentially delaying their operations. This challenge has been mitigated by government’s intervention through compulsory land acquisition.

**Financial risks**
Financial risks were ranked as the third risk IPPs encounter in their set-up projects. Overall, the severity of this risk category was ranked to be “moderate” by the respondents. The key risk factors that constituted this category include taxation changes, Availability of bank financing for the project, Availability of financial support for the project, breaches of contracts, inflation, changes in currency prices and reduction of financial support. In Ghana, the susceptibility of the local currency to the US dollar, as a result of the exchange rate, has been a constant threat to IPPs’ source of recovery – utility tariffs. As a result of foreign exchange losses, the local currency is weak against the US dollar, this has impacted, significantly, the revenues of the IPPs. To keep with the times however, a quarterly review of tariffs has been instituted and has been operational since January 1, 2014. Alternatively, the impact of this risk could be mitigated by sharing the risk between government and IPPs by setting thresholds for higher or lower revenue changes when the risk eventuates. For example, the IPPs could bear the cost of the financial risk event caused by exchange rate under 5 per cent, while the government assumes responsibility for exchange rate fluctuation above 5 per cent (Ke et al., 2010).

**Transport/construction/completion risks**
The severity of risks such as very rapid technology development and related change of price for installations, Unavailability of sufficient amount of skilled labor, Incomplete or inaccurate cost estimate, Incomplete approval and other documents, Inadequate project scheduling, High performance or quality expectations and excessive approval procedures in administrative government departments in this category were deemed to be moderate by respondents.
Renewable energy projects are capital intensive and represent a significant investment commitment. The rapid technology development and related change of price for installation has been noted by the respondents as a key risk factor in this category. As noted by Majano (2014), renewable energy technologies has seen an increased use as the main stream source of energy globally accounting for more than 40 per cent in generating capacity. Even though renewable energy technologies are said to be economically competitive, its global emergence has not been uniform. The manufacturing and use of these technologies have seen its dominance in China, Europe and North America (Majano, 2014). Building a renewable energy power plant outside of these regions imply that the plant and its installation fixtures require importation. As such, IPPs intending to build renewable energy projects in Ghana are confronted with the cost of importing these technologies, with their attendant difficulty in obtaining clearance at the ports, which is further delayed by the long documenting processes at the ports.

**Market risks**

From the study, the key risk factors identified under this category comprises of risk factors such as: split incentives; demand fluctuation; drop of prices in the energy market; and risk of bankruptcy during the contract period (Mosannenzadeh et al., 2017). Overall, this risk category was deemed to be low in terms of its criticality. However, these risks are not within the control of the IPPs as their occurrence are as a result of market conditions and could differ between countries.

Energy price distortion and risk of bankruptcy during the contract period were deemed to be moderate among the four risks constituting this category (Table III). Energy price distortion occurs through government regulations to reduce international price volatility (Shi and Sun, 2017). Energy price distortions, which could occur in the shape of subsidized energy could reduce the competitiveness of renewable technologies and alter the appreciation for the real value of energy efficiency (Mosannenzadeh et al., 2017). As a result, users’ appreciation of energy use reduction is impacted, indirectly increasing the cost of operations of IPPs. A study by Shi and Sun (2017) found that energy price distortions as a result of government control could impact an economy negatively, as a result of the induced distortion.

Another risk in this category is the risk of bankruptcy of the IPPs during the execution of the contracts. IPPs in Ghana, like others worldwide, are guided by a PPA under a build, own, operate and transfer arrangement. The PPA provides the framework of terms of the agreement including the period of the contract. They build and sell the power to the primary national utility power distributor, PDS, as the off taker. The PDS is then responsible for the sale of the generated power, including submitting proposals to the PURC for the determination of the price. However, the utilities have often complained about the unrealistic nature of the prices at which the power is sold to consumers. Furthermore, other challenges such as distribution losses and the public-sector debt to the utilities, have often remained the bane of players in the power sector. These challenges have left the utilities in precarious financial conditions, threatening the sustainability of their operations and their ability to invest more in infrastructure development.

**Environmental risks**

Overall, the risk severity of these risks was noted by the respondents to be low. This is not surprising because renewable energy sources are being favored worldwide as a result of the need to limit harmful emissions on the environment. The environmental performance of renewable energies is increased substantially as a result of increased
efficiency and longevity. Even though all sources of energy pose some risks to the environment, conventional sources such as fossil fuels – oil, coal and natural gas – poses greater risk to the environment compared to renewable energy sources (Klugmann-Radziemska, 2014). For instance, wind energy is noted to possess substantial environmental benefits including, low water or air emissions, no production of hazardous substances, no production of air pollutants or greenhouse gases, significant savings on external costs of conventional fossil fuel-based sources of energy generation (Jaber, 2013). Similar renewable sources of energy such as solar, biomass, bio-fuel, landfill gas, geothermal energy, sewage gas and ocean energy offer other environmental impact advantages. However, the benefits that Ghana accrue from these renewables can be described to be fairly minimal as the installed capacity of renewables, compared to the conventional sources, is marginal. According to the EC of Ghana, out of the total of 3,774.6 Megawatts installed capacity, only 22.6 Megawatts (VRA solar, BXC solar and Safisana biogass) are renewables (Energy Commission of Ghana, 2017).

Conclusion

The purpose of the study was to assess the key risk factors affecting renewable energy of IPPs set-up project in Ghana. The study identified strategic and business risks, policy and regulation risks as risks with high severity impacts on the setting up of renewable energy plants by IPPs in Ghana. Within the study milieu long and complex procedures for authorization of project activities (strategic and business risk) present a key risk factor. Firstly, it is worthy to point out that these procedures are very important and necessary to ensure an efficient system and prevent issues related to corruption. However, due to the time-consuming nature and latent setbacks associated with the procedures, huge capital invested may not recouped within the specified payback period. This is exacerbated by the volatile nature of Ghana’s currency against other currencies such as the US dollars. Secondly, stability of the policy environment and difficulty in obtaining rights to land are risks that IPP need to manage. In Ghana, past events have shown that it is difficult to maintain the autonomy of the regulatory agencies. For example, setting of tariffs in the past has been an issue, with some describing such tariffs as unrealistic. The inability to effectively plan with stability in tariff setting presents a difficult situation for IPPs who seek to recoup their investment through tariffs. In addition to regulatory control, is the regulation of the land tenure systems that presents difficulty in assessing rights to land to set up. Other risks such as financial risks and construction and completion risks were deemed to be moderate, whereas market risks and environmental risks were identified to possess low severity. These risks represent categories of latent risk factors identified from the literature. Overall, this study exposed the existence of several risks that investors in the energy sector have to contend with in their quest to set up renewable energy plants in Ghana. Finally, the findings of this study provide a prodigious opportunity in the formulation of strategies to mitigate the impacts on new investments. The risks identified in this study represents factors new investors are likely to face in the power generation sector. As such it provides a great base of knowledge for the authorities in the energy sector in their promotion of investment in the Ghanaian energy sector. It further provides investors looking to invest in Ghana’s energy sector with adequate information in respect of the existing risks to surmount in their investment efforts.
References


Further reading


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