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Multi-storey residential buildings and occupant’s behaviour during fire evacuation in the UK

Factors relevant to the development of evacuation strategies

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Abstract

Purpose – The purpose of this paper is to investigate human behaviour during fire evacuations in multi-storey residential buildings through a focus on the challenges and obstacles that occupants face. In addition, the paper aims to study all the various behaviours that are relevant to the evacuation strategies/plans in the UK of multi-storey buildings in large cities.

Design/methodology/approach – A literature review was conducted to identify the factors occupants face and also the decision making of occupants regarding the methods of egress. A mixed methods research was adopted using interviews and a questionnaire survey. The findings from the interviews and survey are benchmarked against the information gathered from the literature review.

Findings – The paper identifies various challenges that occupants face when evacuating a multi-storey residential building. In terms of the decision-making process, the research results evidence that occupants could be given more information on the evacuation procedures within their specific building. The paper also finds that occupants remain reluctant to use a lift during evacuation in fire event, irrespective of any signage clearly stating that is appropriate to do so in the context of modern lift technology.

Originality/value – This paper contributes to the body of knowledge available on the evacuation of multi-storey buildings located in large cities within the UK, outlining the potential areas for future research, focused on providing an insight of the behavioural decisions made by the occupants make when evacuating a building in the event of a fire.

Keywords Evacuation, Human behaviour, Decisions, Egress, Lifts, Multi-storey

Paper type Research paper

Introduction

Fire safety has consistently been a vital consideration when designing multi-storey buildings and, given the specific environment of such buildings, human behaviour during an evacuation process has long been considered a key factor in a successful evacuation (Proulx, 2001). Sekizawa et al. (1999) suggested that some key factors are the method through which occupants react to fire cues, the motives they are given to commence evacuating and the choice of evacuation route (typically choosing their usual route of moving around the building or a route identified as being “safe” rather than one that was close). While there is a considerable body of literature relevant to the evacuation of multi-storey buildings, some of this is inevitably dated, particularly in the context of materials development, enhancements to
existing technologies, emerging new technologies and a deeper understanding of the psychology of human behaviour, particularly in the context of group dynamics. Ronchi and Nilsson (2013), for example, considered not only the individual use of egress components but also the combined use of such egress components as stairwells and elevators along with other means of escape that would not be typically regarded as “traditional” (sky-bridges, helicopters, etc.). However, Nilsson and Kinateder (2015) postulate that data on the behaviour of occupants in a fire situation are generally collected using case studies that are consistent with the majority of the literature reviewed. Nilsson and Kinateder further suggest that controlled experiments can also be used to establish relationships in this context. In addition, the use of interview techniques, as used by Shields et al. (2009), appears to be a relatively common method used in fire evacuation occupant behaviour studies.

Human behaviour within a fire has been examined through both the review of past evacuation situations and simulations. Past evacuations which suggest that any decisions made within the conditions are a result of a decision-making process and not based on random actions (Kuligowski, 2009) and the use of evacuation models that can predict occupant evacuation behaviour. In addition to this, Proulx (2001) opines that the behaviour of the occupants will depend on the characteristics of not only the occupant, but also the building and the fire. Proulx (2001) further states that despite adequate fire safety systems being in place, they can often fail due to inaccurate predictions and expectations of how occupants will behave during a fire. Barber (2010) asserted that occupants’ behaviour differs when they class themselves as being at “home”, at “work” or in a social space; when occupants regard themselves as being at “home” they may show a reluctance to evacuate what they perceive to be a safe space until such point as they are sufficiently motivated by a perception of being directly threatened by a fire. Using stairs as the only route of egress during a fire can lower the evacuation speed as well as tire the occupants especially the elderly and sick (Chen et al., 2014). This theory is supported by Heyes (2009) who explains that during an evacuation of a multi-storey building, using only stairs can be impractical due to the ageing population and obesity problems within the UK. To improve this problem, lifts have been proposed and used as methods of egress in multi-storey buildings. Galea (2014) suggests that past studies show that building evacuation speed can be increased by 50 per cent through the combination of lifts and stairs. However, this figure is based on an assumption that if lifts are available then they will actually be used by occupants as a means of egress during an evacuation. This assumption can be dangerous, as Noordermeer (2010) suggests that various factors must also be considered such as how people respond to an emergency, how they interpret the information and directions given and will the fire escapes be used for the intended purposes.

This paper will examine the possible behavioural decisions occupants could make when evacuating a building. The Grenfell disaster exemplifies how occupants behaviour can be affected by their interpretation of the evacuation instructions received when they are in a situation of interpreting such instructions without any “expert” or authoritative input (such as they may rely on when being “marshalled” out of a work environment) within their own homes that contain items of both financial and emotional value (LeGood, 2017). A further consideration is one that some may regard as being “sensitive” (a possibility that may explain the relative lack of data and research in this area) is the nature of occupancy in multi-storey buildings typical of large UK cities. Whilst it is fully acknowledged that relevant and reliable data are scarce, fires such as that at Grenfell Tower have raised awareness of the possible extent of cultural diversity present in such buildings (Bulman, 2017). Therefore, the aim of this research is to explore the perspectives on human behaviour during a fire evacuation of a multi-storey residential building in the UK.

Fire safety in multi-storey buildings
High-rise buildings are complex and therefore require extensive fire safety measures to be incorporated when designing the building. Heffelmire et al. (2016) state that a key challenge for
providing fire safety in a multi-storey building is ensuring that all fire safety systems such as alarms, smoke control and egress systems can sufficiently work together in an integrated system manner. Bengtsson et al. (2008) agree that the consequences of any failure of a building’s fire-related technical systems and the time of the fire service’s response both become more critical in multi-storey buildings. As such buildings have tended to become ever-taller, the challenges presented to both the fire service (such as insufficient reach of fire ladders – in 2017 the longest reach “ladder” in the UK (the Ariel Ladder Platform) had a reach of 42 m; 25 m shorter than the height of Grenfell Tower) and their occupants also increase.

Cowland et al. (2013) suggest that implementing a performance-based design for each multi-storey building allows a rational approach to both life safety and property protection objectives. Identification of specific goals, objectives and performance requirements will allow an engineer the scope to demonstrate the achievement of a required performance. When providing fire safety requirements for multi-storey buildings, it is vital to ensure that a thorough study has been undertaken (Edgar and Chow, 2011). Moreover, when designing a multi-storey building in the UK, the structure must adhere to certain regulations and standards to ensure safe design and construction of the building. The current regulations in the UK are Approved Document B of the Building Regulations 2010 which defines a tall building as any with a top floor height of 45 metres or more. These documents provide legal guidance on fire safety such as stairway widths, ventilation, fire doors and escape routes. Before 2005, fire safety was covered by circa 70 pieces of legislation such as the Fire Precautions Act 1961. It was decided that the numerous forms of legislation should be simplified, thus leading to the creation of the Regulatory Reform (Fire Safety) Order 2005 (Firesafe.org.uk, 2011). For multi-storey residential properties, the Housing Act 2004 must also be adhered to.

The World Trade Centre (WTC) events of 11 September 2001 led to a concern for occupants when evacuating a multi-storey building; the event provided a trigger to reconsider the use of lifts (elevators) for evacuation (Proulx, 2004). Noordermeer (2010) agrees that the events of 11 September 2001 acted as a catalyst to discuss the implementation of lifts in more depth.

The use of lifts for evacuation in high-rise buildings can reduce evacuation times from 2-3 hours to 15-30 minutes (Siikonen and Hakonen, 2002). Older, existing lifts were not designed for use in fire situations and consequently the standard instruction to occupants was that, if a fire should occur, they should use the stairs, not the lifts, as an egress route (Haitao et al., 2012). However, with the improvement of lift performance it is now becoming feasible to use this technology as a means of evacuation. Nonetheless, Klotte et al. (1992) suggest that designing and constructing suitable lifts for evacuation is, in effect, only 50 per cent of the job; occupants of the building must also be prepared to use the lifts in order to ensure a reduced evacuation time. It should be noted that there are numerous definitions for a variety of “tall” buildings, ranging from multi-storey to mega-tall (Designing Buildings, 2017) and that these may differ between countries. In this research, the term “multi-storey” is used as a generic descriptor of any building that is one storey or greater in height (so as not to exclude the occupants of any specific height (storeys) of building). However, it is accepted that, in the UK, the general expectation would be that the majority of multi-storey buildings would be described as being in the one- to nine-storey group, although there is no data in the literature that conclusively evidences this. In addition, the “normal” expectation of a number of storeys within which the majority of tall buildings would sit varies from country to country. A recent analysis of new tall building construction in London, for example, found that the majority of such buildings were in the 20-29-storey category (Hearn, 2015). London can also be shown to contain at least 618 buildings of ten storeys or greater, whereas New York has at least 6,080 such buildings (Skyscraperpage, 2017). Given that many may regard New York as the spiritual home of the skyscraper, it may be surprising that the median number of floors for such buildings is a relatively low 16 (Hickey, 2014).
Human behaviour during a fire evacuation

Although adequate fire safety systems are used in most buildings today, fire can still occur; during the period 2009-2013, there were an average of 14,500 fires, 40 deaths and 520 injuries per year in US multi-storey buildings (Ahrens, 2016). Proulx (2001) suggests that such deaths and injuries largely result from incorrect assumptions with regards to the fire-related behaviour of the occupants of such buildings. In the context of an overall fire situation (typically consider to comprise three phases: Phase 1 – period between a fire starting and being detected; Phase 2 – period between occupants being aware of a fire and their making the decision to leave the building; and Phase 3 – period between the evacuation commencing and the full evacuation of a building. This should not be confused with the concept of a phased evacuation as considered by Adler).

A study of 225 multi-storey occupants showed that 93.33 per cent of those surveyed believed that there would be panic during a fire situation (Cordeiro et al., 2011), a figure which rose to 96 per cent within the subset of the sample who had actually experienced such a fire. Lo et al. (2000), however, suggest that panic is a misconception and research has shown that, during the initial stages of a fire, occupants behave in a controlled and rational manor. This theory is supported by Proulx (2001) who explains that there is little evidence of panic in actual fire situations. In addition, Winerman (2004) argues that “panic” is simply not the most appropriate description for the feeling that occupants report experiencing – they are fearful; a state of mind that can result in some unexpected behaviours, such as trying to exit by whatever route they entered the building. If greater attention was given to human behaviour during a fire, then many unexpected behaviours could be eradicated. Once occupants have heard the alarm, seconds or minutes can pass before they begin evacuating (Proulx, 2003).

One of the arguably more unexpected behaviours that have been identified is that people will tend to try and help each other (altruism), particularly when they are familiar to each other. The altruistic aspect of evacuation behaviours has been known about for some time (the social categorisation theory (Tajfel and Turner, 1979) and the social identity model (Reicher, 1987) of crowd behaviour, for example, identified not only altruism but also self-sacrifice) and yet the expectation of panic remains a common belief. This belief appears, at least in part, to be an outcome of overly exaggerated reporting by media that seem unable to differentiate between fear and panic (Galea, 2012).

Human behaviour during a fire evacuation of a multi-storey residential building differs from that of an occupant in a commercial multi-storey building, due to the form of construction used in each case. People will react when they perceive a fire cue such as smell, noise from other occupants, sight of flames or smoke or a fire alarm (Kuligowski, 2009). As residential occupants will generally live in fire-tight units, they are unlikely to perceive cues that would be available to commercial occupants (in a typical open-plan office space) such as smell, sight or noise from other occupants who are already aware of a fire; occupants need to be informed of the fire before they can react (Lo et al., 2000).

Galea (2014) proposes that research into the evacuation during the WTC attacks of 2011 showed that the occupants did not have adequate information when evacuating the building. For example, the occupants evacuating the WTC would have not been specifically informed to follow the directions provided by emergency signage; only 38 per cent of occupants evacuating “see” the emergency signs when evacuating, but 100 per cent of the occupants will follow the signs if they see them, thereby suggesting that emergency signage is not sufficiently effective in securing occupants’ attention. This problem may simply be that, as Johnson (2005) argues, occupants will ignore emergency signage and instead retrace the route in which they entered the building. The decision to use a familiar route rather than follow the signs and take an unfamiliar (and therefore presenting an unknown level of uncertainty) path is a feature that occurs often that leads to many accidents. This has, in turn, led to an increasingly sophisticated approach to the incorporation of risk perception (RP) models in connection with
seeking to more fully understand the decision-making behaviour of occupants during a fire situation. Kinateder et al. (2015), for example, suggest that RP is essentially the personalisation of risk within a specific event context, and is a process that, as with most human processes, is subject to cognitive biases and emotions. If such a RP model is accepted, it may provide insights into the “value” of familiarity (as a cognitive bias?) within the decision-making process; commercial building occupants are (in many countries) legally required to engage in regular fire evacuation drills (thereby “creating” a familiar exit path regarding which they have minimal uncertainty), whereas private multi-storey building occupants are typically only exposed to evacuation signage (rather than becoming familiar with an evacuation route).

Traditionally it is assumed that lifts should not be used as a method of evacuation. However, increasingly this idea has been discarded due to the need for faster and more efficient (than the traditional stairwell routes) forms of evacuation (Ronchi and Nilsson, 2013). To sufficiently design a lift system for evacuation use, designers must possess an understanding of the occupant’s behaviour when using the lifts; a common assumption is that occupants will wait indefinitely for a lift to arrive, which in fact does not truly reflect the behaviour of people in that situation (Heyes, 2009). In addition, fire engineers often assume that if lifts are available to occupants and they are made aware that they are safe to use, then they will use them. However, a survey of 424 people by Galea (2014) showed that even if occupants were well informed and the lifts were safe to use in a fire situation, only 33 per cent of people would consider using them. This finding may represent a behavioural change from the findings of an earlier study by Canter (1996), who surveyed a sample of 77 people who had been involved in a fire evacuation where lifts were available for evacuation – 85 per cent people used them. As previously mentioned, however, decision making in a fire situation is a complex interaction between cognitive biases, personal emotions, quality of information available and familiarity that arguably results in varying perceptions of risk, and therefore varying decisions regarding the evacuation behaviour.

Heyes (2009) proposes that the main concerns occupants have for not using lifts to evacuate a building are:

- being trapped in the lift if the power fails;
- concern that smoke or fire may enter the lift;
- the possibility that the lift could fail causing the lift to fall; and
- the time it takes to wait for the lift.

Hall (2010) agrees with the waiting time concern, suggesting that remaining stationary while waiting for the lift can easily agitate many occupants (again, fear, rather than panic). Moreover, the probability that an occupant could reduce the evacuation time by waiting for a lift, rather than immediately using the stairs, largely depends on the floor that the occupant is on; the higher the floor, the more probable the evacuation time will be shorter when using a lift travelling at a typical speed. A 2009 guidance document for the Department for Communities and Local Government compared typical speeds for stairwell and lift evacuation routes, and found that, as the evacuation starting point moved up the building, the lift provided an increasingly faster evacuation than use of the stairwell, even when the larger “carrying” capacity of the stairwell (along with other factors) was taken into account (Charters and Fraser-Mitchell, 2009). Even though such information is known to fire engineers, the information provided to occupants is typically minimal (Hall, 2010). Galea (2014) conducted a survey of which 424 participants were asked about the amount of time they were willing to wait for a lift during an evacuation, the majority of people survey specified a finite time that they would be willing to wait, depending on the floor height, crowd density and the expected (not the calculated, as per Charters and Fraser-Mitchell, 2009 for example) waiting time.
Proulx *et al.* (2009) suggest that several factors can influence whether an occupant uses a lift for building evacuation, varying from person to person depending on the occupant’s knowledge of the egress routes and previous experiences of evacuations. Research has shown that most decisions are based on what the occupant estimates (typically as a non-expert, therefore the validity of such an estimate can be regarded as low) is that fastest route to evacuate the building. A method of increasing the efficiency of an evacuation is by displaying the estimated evacuation of both the stairs and lifts. This will allow the occupants to make an informed decision.

**Methodology**

To achieve the research aim, both quantitative and qualitative methods were used, and both interviews and questionnaires were utilised to collect data for the research, with both adopting an essentially semi-structured approach. This allowed for a more comparative approach to the analysis of the data/information gathered than would be the case with an interview or questionnaire only methodology. In addition, an expert evaluation exercise with respect to the initial questionnaire design (informed by relevant literature) was carried out as a means of establishing if any questions needed to be edited/removed or added. Both the interview and questionnaire designs are discussed in more detail in the following sections.

**Questionnaire design**

Following research into questionnaire techniques and design the researchers decided on a questionnaire design comprising both open and closed questions in the manner of Fridolf and Nilsson (2012), who combined closed and open approaches within a single instrument when studying fire safety in underground rail transportation systems. The questionnaire also included a section that the participants could use to comment on anything regarding the research. A total of 72 people completed the questionnaire, the participants were occupants of multi-storey buildings, and were constituted as samples of individuals that had or had not been involved in a real fire evacuation situation, thereby representing two data sets to facilitate a comparison. By comparing the two situations, an insight can be gained into fire situation behaviours of individuals who have experienced an evacuation, and therefore “know” how they will react, as opposed to the individuals who have not had that experience and therefore believe how they will react.

The questionnaire and interview were designed so as to provide insights, from both the expert and non-expert perspectives, on key issues identified within the literature. These issues can be summarised as covering five areas:

1. challenges facing evacuees during a fire situation;
2. quantity of information provided to evacuees;
3. extent of occupant reluctance to evacuate immediately;
4. factors affecting occupant decision making during an evacuation; and
5. extent of evacuee reluctance to use lifts, even after being informed it is safe to do so.

The questionnaire was designed to be completed as an online survey thereby allowing a large number of participants to complete the questionnaire, whereas the interview was intended to be undertaken by a small number (three) of experts from different countries.

Prior to releasing the questionnaire, it was evaluated by relevant experts in the field of the subject, so as to ensure the validity of the questions before being released to survey participants. The evaluation identified some questions as difficult to understand and therefore in need of simplification to ensure the relevance of any answers. In addition, some questions required a small degree of re-wording, and it was suggested that the total number of questions
needed to be reduced. A final suggestion was that some question response categories should be changed so as to facilitate analysis of the answers. All of these actions were implemented to ensure the final questionnaire was clear and able to supply more relevant results.

Interview design

The interview method was intended to complement the questionnaire in that it focussed on gathering the expertise of fire engineering experts, while the questionnaire focussed on non-experts (the occupants). As stated previously, the questionnaire was intended to be as available as possible to non-experts, so as to collect a large data set. The interview, however, took the opposite approach in that it was completed by three experts. In this context, there is a need to acknowledge the debate concerning the relative “value” of expert and non-expert knowledge. Rae and Alexander (n.d.), for example, note that, when safety-related risk is the focus, “[...] the opinions of experts are given greater weight than the opinions of non-experts”.

By obtaining the responses of both experts and non-experts with regard to a number of specific issues this research aimed to determine the extent of any difference in terms of knowledge (where knowledge (applied information) is considered to be the combination of data (measurements) and information (data given meaning) (Paunović, 2008)) about those issues.

Arguably the key aspect of value applicable to this research is that experts and non-experts (novices) learn differently from what appears to be essentially the same experience. In a multi-storey building fire situation, individuals can be assumed to base their decision making on their existing knowledge – do not use the lifts, for example; an expert may well have appropriate knowledge to recognise a “safe” lift, whereas a non-expert may rely on their knowledge of having been instructed that lifts should not be used during a fire situation. In each case, the behavioural outcome would differ. However, the expert typically has the luxury of making a behavioural decision whilst accessing relevant data and information (knowledge) in a safe environment. In comparison, the non-expert sample within this research was expected to evidence relatively little knowledge (in terms of equivalency to the experts) and also be affected by the immediacy (in terms of both their environment and the perception of a possible threat) of the required decision. Weber and Chapman (2005), for example, investigated the possibility of a relationship between the time available to make a decision and the level of certainty/uncertainty about that decision; does delaying a decision (such as when to leave a dwelling and commence evacuation) create uncertainty?

Yin (2009), Kumar (2014) and Saunders et al. (2015) concur and postulate that a semi-structured interview is the most efficient method of interview through the use of focussed questions. Several questions were recognised as possible to be answered by a simple “yes” or “no” (such as: Are occupants provided with sufficient information on evacuation procedures?), although the expectation was that the probability of this happening was low. However, the interviewer used such questions in combination with the scope to probe the (expert) interviewee for more in-depth knowledge in the event that their answer was no more than a “yes” or “no”. The interviews were designed consisting of five focussed questions, with three fire engineering experts invited to participate as interviewees.

Data analysis

The questionnaire findings are presented as a series of graphs showing the occupants responses. Where appropriate, the responses were analysed using the relative importance index formula (Equation (1)), as created using Microsoft Excel:

$$\text{Relative importance index (\%)} = \frac{5(n5) + 4(n4) + 3(n3) + 2(n2) + n1}{5(n1) + n2 + n3 + n4 + n5} \times 100$$ (1)
with $n5 =$ highly concerned; $n4 =$ slightly concerned; $n3 =$ neutral; $n2 =$ not really concerned and $n1 =$ not at all concerned. The occupants’ answers were inputted into Microsoft Excel and were checked thoroughly to ensure no inputting errors had occurred. The interviews were conducted through an online audio conversation, and subsequently transcribed in readiness for the application of the content analysis technique.

Results, analysis and discussion
The purpose of this study was to explore human behaviour during a multi-storey residential fire evacuation situation, the decisions occupants make during such a situation, and their choice of egress methods. The data and information gathered from the questionnaire responses and interviews were then analysed in accordance with the methodology discussed previously. The process of distributing (online) the questionnaire and then collecting data and information from the responses took approximately two weeks. As part of this process, it was determined that the questionnaire typically took approximately ten minutes to complete, and that a total of 78 questionnaires were completed.

Questionnaire results
Q1 established the age bracket of each participant, and the building floor on which they resided. Figure 1 shows the results of the age brackets of participants; the majority of respondents were between the ages of 25 and 34.

Figure 2 displays the floor of the building on which the occupants lived; 62.82 per cent of occupants resided between Floors 1 and 9. The results also evidenced that there were 0 per cent of respondents living on Floors 50 or above.

Q3 asked if the participant had previously been involved in a real-life fire evacuation situation while living in a multi-storey building; 30.77 per cent of respondents confirmed they had been involved in a real fire evacuation situation. This could affect the occupants’ decision, as it would reasonably be expected that occupants with previous experience of fire evacuation may make different decisions to those that have not. Moreover, Cordeiro et al. (2011) surveyed 225 people and asked the occupants that had been previously involved in a fire evacuation situation if their reactions would be the same (if they were faced with a further fire evacuation situation) and 54 per cent answered affirmatively.
Q4 investigated the decisions that participants make during an emergency evacuation of a multi-storey residential building. Figure 3 shows what method of evacuation occupants would choose during a fire evacuation:

1. 66.7 per cent would definitely take the stairs and 16.67 per cent would probably take the stairs; and
2. 7.69 per cent would probably take the lift and 0 per cent would definitely take the lift.

Similar results were produced in a survey undertaken by Galea (2014) of 424 people, of which two-thirds said that they would not consider using a lift to evacuate despite being informed that the lifts were a safe and acceptable option. These results show that most occupants are still reluctant to use a lift as a method of egress during an emergency evacuation, and that the stairs would be more than likely used by most occupants. Occupants need to be educated more on the using a lift for evacuation, as in most cases signage alone is not enough.

Figure 4 shows that the higher the floor of residence, the more its occupants are likely to use the lift:

1. 0 per cent of occupants on Floors 1-9 and 10-19 answered that they would “definitely” or “probably” take the lift; and
2. 30 per cent of occupants on Floors 20-29 answered that they would “probably” use the lift; and
3. 42.86 per cent of occupants on floors 30-39 would “probably” use the lift.

The data show that occupants residing in higher floors are more likely to use a lift in an evacuation situation. These results compare well to the data collected by Heyes (2009) of 229 respondents, the analysis of which showed a similar linear relationship between floor level and the percentage of respondents that would use the lift as a method of evacuation.

The results shown in Figure 5 show the comparison of the selected method of egress and the age of occupants. This illustrates that the older the occupants, the less likely they are to use the stairs to evacuate during a fire situation. This decision would most likely be down to the physical capabilities of older occupants, which would lead to evacuation being difficult and time consuming. While there is no specific evidence within the responses, there may
also be some awareness of the tiring nature of walking down multiple flights of stairs. The concerns of evacuation of elderly or impaired occupants was mentioned by one participant of the survey, the participant went on to explain their previous experience of evacuating occupants requiring assistance, in which it was found such an evacuation can take a long time. Furthermore, the results show that 0 per cent of occupants in the 18-24 and 25-34 age brackets would take a lift during a fire evacuation. This suggests that younger occupants take the stairs regardless of what floor they reside on.

Q5 sought to establish what the participants’ initial reaction would be to a fire alarm in the middle of the night. Figure 6 shows the results of this question.

These results show that only 21.79 per cent of the respondents would evacuate immediately, a result that correlates to a study in Egypt of 62 multi-storey residents who were asked “what you do when you hear the fire alarm”. The results showed that evacuating the building immediately had a relative important index of 62.39 per cent (Gerges et al., 2017).
The results here show that there are issues in trying to get occupants to immediately evacuate multi-storey residential buildings. Moreover, Gerges et al. (2017) showed that the number 1-ranked factor of occupants was to “Ask neighbours regarding if there is a fire (i.e. Investigate)”, this factor had a relative important index of 84.33 per cent. This coincides with the 41.03 per cent of participants in this research that answered that their initial reaction would be to wait until they were sure of a real fire. Research of 225 participants by Cordeiro et al. (2011) showed that 65 per cent of occupants first reaction to a fire alarm was “find out what was happening”. These results show that occupants need to be confident of a real threat before they will immediately evacuate the building.

Q12 asked the occupants “If there was an alternate alarm in place that went off when there was a fire within (close) proximity, would this increase the speed of your evacuation?” The results are displayed in Figure 7.

Figure 7 shows that 73.08 per cent of occupants would definitely or probably evacuate quicker. When the response of those occupants presented in Figure 6 that did not answer “evacuate immediately”, it can be shown (Figure 8) that an alternate alarm would
either definitely or probably increase 75.44 per cent of occupants’ evacuation speed. However, 11.48 per cent probably would not evacuate quicker and 13.12 per cent answered that it would not make a difference to their evacuation speed, thereby evidencing that some people will always be reluctant to leave their residential properties immediately. Nonetheless, the results show that most occupants would actually evacuate quicker with an alternate alarm, if that alarm would make the occupants aware that the fire was a serious threat and not a fire drill. This in turn would improve the evacuation speed for the majority of occupants. This point was highlighted by a responder who stated that different alarms in relation to differing proximities of a fire would help the evacuation process.

Q6 establishes if a resident would use a lift as a method of egress during a fire evacuation situation. Only 1.28 per cent of occupants would “strongly agree” that they

Figure 7. Results of evacuation speed if an alternate alarm was in place

Figure 8. Would an alternate alarm make a difference to occupants' evacuation speed?
would use a lift. Moreover, 46.15 per cent of participants answered that they “strongly disagree”. Overall, the results show a clear indication of occupants’ reluctance to use a lift during a fire evacuation.

Q9 asked the occupants if they would use stairs as a method of egress during a fire evacuation. In this aspect, the results were as were expected, based on the literature; 66.67 per cent “strongly agree” and 23.08 per cent “agree” that they would use the stairs during a fire evacuation. Only 5.13 per cent of occupants answered “disagree”, which is most likely down to a disability or being physically incapable of using the stairs.

Q10 states that to ensure an efficient evacuation of a multi-storey building, it is vital to give occupants a sufficient amount of information regarding the fire evacuation procedures within their building. This section of the research investigated whether occupants considered themselves to be well informed on the fire evacuation procedures in their buildings. The results are displayed in Figure 9.

Figure 9 shows that 46.16 per cent of occupants “strongly agree” or “agree” that they are well informed regarding fire evacuation procedures in their building. Moreover, 23.08 per cent “disagree” and 11.54 per cent “strongly disagree” that they are well informed on their fire evacuation procedures; a worrying statistic, as a lack of information can have a major impact on the success of an evacuation should a real fire occur. Three participants of the questionnaire commented that no evacuation details were provided regarding their multi-storey residential building. However, these results present a more positive picture than does the research completed by Lo et al. (2000) of two cases in Hong Kong, which showed that a total 68.9 per cent of occupants had not received any training on evacuation procedures. Additionally, Cordeiro et al. (2011) asked 225 occupants in Portugal about their knowledge of evacuation plans, and only 35 per cent answered that they were aware of their building’s evacuation plan. These results show that occupants need to be more educated/informed regarding their building’s relevant fire safety and evacuation procedures. If clear information is given to occupants then they will be aware of the most efficient method of evacuation, thereby mitigating some of the various factors can affect how an occupant evacuates.

Figure 9.
Occupants are well informed on the fire evacuation procedures within their building.

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.08%</td>
<td>Strongly agree</td>
</tr>
<tr>
<td>23.08%</td>
<td>Agree</td>
</tr>
<tr>
<td>23.08%</td>
<td>Disagree</td>
</tr>
<tr>
<td>11.54%</td>
<td>Strongly disagree</td>
</tr>
<tr>
<td>0.00%</td>
<td>(Did not answer)</td>
</tr>
</tbody>
</table>
Within Q11, the occupants were asked which factors would most likely affect their decision making when choosing a method of egress during a fire evacuation. Figure 10 shows the occupants’ responses:

- the main factors that occupants base their choice of egress method on is “The emergency evacuation signs” (37.18 per cent) and “the familiarity of the route” (35.90 per cent);
- the least common choice is “The route that requires the least amount of physical work”; only 1.28 per cent of occupants chose this factor which could be due to issues displayed in previous results that some occupants may have a disability or physical incapability; and
- only 7.69 per cent of occupants answered that “the least congested route of egress” was a factor that can affect their choice of egress method.

These results could indicate that other occupants will continue to evacuate using an egress method that is highly congested despite other options being available. Research by Lawson (2011) asked the participants to rate how influential different factors were on their choice of egress, with the factors being rated from 1 (not at all influential) to 5 (very influential). The results showed that occupants rated “other occupants” as the most influential factor with an average rating of 5, followed by “distance” and “instruction from authority figure” with an average rating of 4. The “familiarity with route” only measured a 3.5 on the influence scale, although Figure 9 shows that this same factor was chosen as the main factor affecting the occupant’s choice of egress. One participant of the questionnaire commented that the use of technology in fire evacuation should be implemented to aid occupants; the researchers here believes that this would be a viable option due to the high number of smart phones being used within the UK.

The last section of the questionnaire asks the occupants to rate their concerns for different hazards relating to lifts and stairs during a fire evacuation situation, the results for the lift hazards can be shown in Table I.

---

Figure 10. Factors affecting occupant’s choice of egress method
The analysis of Table I shows that the main concern when using a lift during a fire evacuation was “being stuck in the lift” (89.60 per cent) followed by “smoke entering the lift” (88.95 per cent). This shows that more information could be given to the occupants regarding the engineering of the lift and its actual level of resistance to fire and smoke. For comparison, Table II displays the results of the occupants’ concerns regarding hazards when using the stairs during a fire evacuation. These results show that “fire entering the stairway” (86.67 per cent) and “smoke entering the stairway” (82.56 per cent) are the greatest concerns of occupants when evacuating using the stairs. This data show that occupants are worried that a stairway could be filled with fire or smoke. A sufficient way to address this hazard would be to install “smart” signs that tell the occupants which egress stairway to take to avoid the fire.

Moreover, “not being physically capable of walking down stairs” (56.86 per cent) ranked number 6 on the table. Heyes’ (2009) research (focussed on San Francisco) showed that 55 per cent of occupants answered “not at all concerned” about not being physically fit enough to travel down many flights of stairs. The researchers suspect that some occupants who state they are not concerned about being physically fit enough to walk down a high number of stairs, may assume they are in better physical condition than they actually are.

### Interview results

Three interviews were completed with experts within the field of fire engineering, one from the UK, one from New Zealand and one from Sweden. Each participant was invited to take part in a 20-30-minute interview which consisted of five questions. One interview was conducted face-to-face, and the other two were conducted via an online call.

The first question asked the interviewee’s opinion on the main challenges that occupants face during a fire evacuation of a multi-storey residential building. Interviewee 1 suggested that the main challenge is occupants not having enough information during the evacuation process. Interviewee 2 agreed that providing information on evacuating the building is one of the main challenges when evacuating a multi-storey residential building. Furthermore, Interviewee 3 explained that the long distances occupants need to travel to...
evacuate high-rise buildings in particular is the main challenge, especially if there are occupants with mobility impairments or disabilities. Interviewees 1 and 3 both mentioned "culture", as this can affect occupants' decisions when evacuating a multi-storey residential building, with Interviewee 1 suggesting that people in the Middle East are not as serious about fire alarms as people within the UK.

The second question of the interview investigated whether occupants are provided with enough information on the fire evacuation procedures within multi-storey residential buildings. Both Interviewees 2 and 3 explained that this depends on the country of the building but the consensus was that information and awareness could be improved within the UK. Interviewee 1 suggested that there is a lack of use of technology during fire evacuations, and that smart phones, for example, could be utilised to improve evacuation efficiency. Furthermore, Interviewee 1 stated that information given by other occupants during a fire evacuation can be inaccurate and during a previous fire evacuation of a multi-storey building a voice communication message stated, “Please evacuate the building immediately” but there was no information given regarding the shortest and safest route to take.

Q3 aimed to find out if the occupants are reluctant to leave their properties unless they are confident of a real threat. All three interviewees agreed that occupants were reluctant to leave their properties with both Interviewees 1 and 2 using the words “definitely”. Interviewees 2 and 3 both argued that the evacuation time from a residential building is higher than that for an office building. All three interviewees suggested that occupants are reluctant to leave their belongings, or will collect them before they evacuate a multi-storey residential building. Interviewee 1 also suggested that occupants tend to look at others as leaders before they evacuate, and their decisions on when to evacuate will be based on their knowledge of fire situations and any previous fire/evacuation experience.

Q4 asked what the main factors are that affect occupants' decisions during an evacuation. Both Interviewees 2 and 3 identified “social” interaction or influence as being a key factor; the information occupants receive from other occupants can impact their decisions. Moreover, Interviewee 1 suggested that the structural layout of the building is a main factor, as it plays an important role on what evacuation route the occupants may take. This point is supported by Interviewee 2 who stated that the environmental condition of the building is critical to finding a way out. Smoke was mentioned by both Interviewees 1 and 2 as important factors than can affect the decision of the occupants; the sight or smell of smoke can change the occupants egress route. Interviewee 2 suggested that the physical performance of the occupant also needs to be considered, especially in terms of mobility, because if the occupant is required to use many stairs to evacuate then their body’s physical performance becomes a factor.

The interviewees were asked in Q5 to explain if they thought occupants were still reluctant to use lifts during a fire evacuation, even if they are deemed safe to use. All three interviewees agreed that many occupants still have the stereotypical view that lifts should not be used, no matter what. All three interviewees suggested that this can also depend on the time an occupant is willing to wait for a lift; previous research has shown that, in general, occupants are not willing to wait more than ten minutes for a lift. Interviewee 1 agreed that waiting too long for the lift to arrive can deter occupants from using a lift. Interviewee 1 also suggested that their personal experience has led to the conclusion that some occupants would not use the lift even if it was safe, due to factors such as:

- not being enough room in the lift for the whole family;
- too many other occupants waiting for the lift; and
- some lifts being out of order, which gave the impression that the lifts were unreliable.
Interviewees 2 and 3 stated that occupants need to be more educated about both fire situation and evacuation procedures and given more information on the use of lifts during an evacuation of a multi-storey residential building.

Conclusions
The aim of the research was to explore human behaviour during a fire evacuation and place such behavioural responses in the context of a multi-storey residential building in the UK so as to suggest the factors relevant to the safe evacuation of residents. The research evidenced that there are various factors that discourage occupants from using certain egress routes. For example, the results of the questionnaire evidenced that fire and smoke entering the stairway are the main factors that affect the use of stairs during an evacuation. In addition, the questionnaire results evidenced that the factors deterring occupants from using a lift are concerns of being stuck in the lift and smoke or fire entering the lift. The interviews also concluded that lifts are still perceived as being dangerous to use during a fire evacuation situation, which is no longer completely accurate as some lifts in multi-storey buildings are designed to allow safe evacuation during a fire. However, occupants need to be thoroughly educated and clearly informed with regard to such factors.

Various issues can affect the occupants’ behaviour during a multi-storey fire evacuation. The questionnaire results showed that the majority of occupants would not immediately evacuate their residence when hearing a fire alarm. Moreover, the results of the interviews stated that this is because occupants are reluctant to leave their personal possessions or property as in many cases the fire alarm is a false alarm or a drill. The results of the questionnaire also showed that the occupant’s reluctance to evacuate immediately once hearing a fire alarm could be reduced through the use of an alternate alarm that indicated a fire was within close proximity. The researchers conclude that this would help the occupants to make more effective decisions in a fire situation and thus speed up the evacuation time of those occupants in closest proximity to the fire.

There are several factors to consider that can affect the occupants’ receipt of “threat” cues during a fire evacuation. The literature review identified that occupants of residential multi-storey buildings may not receive cues such as smell, sight and noise, as they generally live in fire-tight properties. The questionnaire results show that most occupants will wait until they are sure a fire is “real” before they evacuate, thereby suggesting that cues such as other people evacuating are not considered until a real fire has been confirmed. The interviews produced results that identified culture as an important factor affecting the interpretation of the cues occupants receive; some cultures are not serious about fire alarms and will not consider an alarm as evidence of a “real” fire situation. Occupants fire responses should be considered to be an important factor to be cognizant of when drawing up evacuation strategies plans for multi-storey buildings.

Recommendations for future research
The researchers acknowledge a constraint when carrying out this research was their limited access to fire engineering experts within the UK. Additional interviews with experts within the UK would undoubtedly add further insights into human behaviour of occupants specifically in the UK.

The research suggests that a further questionnaire could be distributed to the occupants that reside in properties having a lift that can be used during a fire evacuation. This will produce detailed results on whether occupants would not use a lift even after being informed that the lift is safe to use. Due to the limited information provided to occupants during the evacuation, the researchers recommend further research is required into this area.

The results of the research have shown that occupants need to be more informed on the fire safety procedures within their building; the research would suggest a possible mobile
phone application that could be used by occupants of a building. The app would update occupants on any changes to the building, such as lifts being out of use, and could be used during a fire evacuation to inform occupants of the safest route to take, ensuring the shortest evacuation time. The researchers also recommend an alternate alarm within a multi-storey building that alerts occupants when there is a fire within close proximity. This would speed up the evacuation decision for those occupants who would usually wait until they were sure of a real fire before evacuating. The researchers believe that the implementation of these recommendations would improve both the level of safety and the speed of a fire evacuation in the context of a multi-storey residential building.

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Further reading


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Factors for the adoption of green building specifications in China

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Abstract

Purpose – Green specifications are some of the most important strategies for energy saving and describe the best practice in the field of sustainable construction. They have great effects on resource saving and environmental protection. The demand of sustainable construction has spurred the emerging and development of green specifications. However, there are many factors that affect the adoption of green specifications in China. Therefore, the purpose of this paper is to investigate the factors that affect the adoption of green specifications in China.

Design/methodology/approach – Based on the comprehensive literature review, a questionnaire survey has been conducted with major stakeholders in construction area to identify issues concerning the adoption of green specifications in China. In total, 18 variables that affect the adoption of green specifications were summarized. Then this study uses factor analysis and mean score method to analyze 18 variables which the authors get from the questionnaire.

Findings – Using the rank analysis and factor analysis, the variables have been ranked, analyzed and categorized into five independent factors. They are summarized as: green technology and techniques; awareness and attitude; policies and regulations; market; and economics. This study provides a variable reference for policy makers to put forward focused policies and incentives for green specifications implementation and industry practitioners to better understand of green specifications adoption in China.

Originality/value – This paper makes a contribution to the understanding of the factors that affect the adoption of the green specifications in China. The results can also contribute to better adoption of green specifications in other developing countries.

Keywords Developing countries, Sustainable development, Factor, Green specifications

1. Introduction

The construction industry has a profound impact not only on economic development and public social life, but also on the natural environment (US Green Building Council (USGBC, 2003)). The construction industry has consumed more global nonrenewable and renewable resources such as water, raw materials and energy, and emitted waste such as air pollution (Tutari and Kucukvar, 2011) or physical waste (Berardi, 2013). Consequently, it is significant to find a sustainable way to reduce waste, improve efficiency and use renewable energy resources in the construction industry. With the rising global attention (Kibwami and Tutesigensi, 2016) and the demand for sustainable construction, building green buildings has been an efficient way as it can minimize the impact on the natural environment and maximize human health. It also uses energy-efficient appliances and systems to utilize fewer resources, like water, electricity, gas and energy, and increases the use of recycled materials, like natural linoleum or bamboo flooring to reduce waste during the construction process (Yudelson, 2009; Zhang et al., 2011). It has been claimed that green buildings can not only give the construction industry environmental, economic and social benefits, but also can provide a sustainable development
opportunity as it can minimize the pollutants, renew natural resources [...] through sustainable buildings. Consequently, the research on the concepts and practices of green buildings has been accepted and adopted both in developed and developing countries (Gou and Xie, 2016).

Green building specifications or guidelines have proved that they are the critical methods for the AEC area as the solution of environmental problems. Hill and Bowen (1997) hold that specifications and contracts are of great importance for sustainable construction. Green building specifications or guidelines are critical principles in the AEC area and can be seen as innovation for future construction projects (Crawley and Aho, 1999). In previous literature, it has been mentioned that specifications should be a promising solution for many environmental problems in the construction industry (Meryman and Silman, 2004; Collins, 1994). Crawley and Aho (1999) emphasize the important effect of green building specifications for environment protection in construction projects. In turn, the increase use of sustainable materials can promote the emergence of green building specifications (Chick and Micklethwaite, 2002).

With the fast development of economy and urbanization, China is experiencing a large-scale construction period. Statistically, new buildings will use 40 percent cement and steel in the world with the amount of 2 billion m² (Qiu, 2010). China has already ranked the second largest building energy user in the world and has been expected to grow fast in the next few years. Besides, compared to developed countries such as the UK or the USA, the life of buildings in China is about 30 years, which is considerably shorter than 80 years in Europe or 44 years in the USA (Hu et al., 2009). Consequently, using green building to alleviate the energy consuming in construction is important. To achieve this aim, green building specifications are the critical guarantee for stakeholders to realize green building construction. China is one of the few countries that make green building specifications according to its own domestic situation. As a typical example of developing countries, China has issued several Chinese specifications for green building/energy-efficient building assessment or design codes (GOBAS-Group, 2003; Ministry of Housing and Urban-Rural Department of the People’s Republic of China, General Administration of Quality Supervisor Inspection and Quarantine of the People’s Republic of China, 2006; Ministry of Environmental Protection of the People’s Republic of China, 2007; Yong et al., 2012). There is little literature on green specifications adoption especially in developing countries. The literature on developing countries including India, Turkey and Indonesia exists, but there is no detailed research on China’s green specification adoption. Despite the recognition of the importance of specifications in the application of green construction, there are no detailed studies that focus on the potential factors that affect the adoption of green building specifications in China’s construction area. Therefore, it is necessary and useful to have a comprehensive investigation and survey. As China is a typical and important developing country at sustainable construction and it has its own different standard systems, conducting some researches that focus specifically on the adoption of green specifications is worthwhile and significant. The research can help green specifications work well and give advice on sustainable construction in developing countries. Consequently, it is conducive to reducing resource waste and facilitating sustainable development in developing counties.

The concept of green building specifications is referred to a series of guidelines, codes or standards, relating to the green constructions with emphasis on the environmental friendliness, together with the concerns on economics and social development. Despite the recognition of the importance of green building specifications in the application of green construction, there are a few studies on the potential factors that affect the adoption of green building specifications in the construction area. In this research, factors of green building specification adoption are investigated through the literature review and questionnaire survey. Therefore, the aims of this research lay in two parts: classifying the general factors concerning the adoption of green specifications in China; and being proposed as a useful reference for the government to drive the adoption of green specifications.
2. Influencing factors for the adoption of green specifications

There were few researchers and practitioners who have investigated the barriers that hinder the adoption of green specifications in construction. In the previous research, the factors such as higher cost, lack of knowledge and awareness of sustainable construction have been listed.

Meryman and Silman (2004) argued three factors were quite important when using specifications for sustainable construction. They identified that economy, policies and techniques were the barriers in the USA sustainable engineering practice activities. High-volume fly ash concrete, recycled concrete aggregates, and supplementary cementitious materials are recommended to overcome the barriers. Abidin (2010) considered that the pace of action toward sustainable application depended on the consciousness, knowledge as well as an understanding of the consequences of individual actions. Lam et al. (2009) categories cost, delay, technical issues, contractual considerations, and management were the factors that influence the adoption of green specifications in Hong Kong. Potbhare et al. (2009) formulated an implementation strategy for the rapid adoption of green guidelines for the developing nations, based on the detailed review of the major green building guidelines globally and contextual information of the Indian society which were collected through a survey questionnaire.

In recognition of these contributions to the knowledge of green specifications in China, and based on the research in the field, an initial list of the identified variables specifically for China was compiled and synthesized in this paper. Table I shows a list of variables summarized from the previous related literature.

<table>
<thead>
<tr>
<th>No</th>
<th>Barriers variables (Bvs)</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>Higher initial cost of GB adoption</td>
<td>Potbhare, Syal, Korkmaz (2009), Potbhare, Syal, Arif et al. (2009), Collins (1994), Lam et al. (2009, 2010)</td>
</tr>
<tr>
<td>V2</td>
<td>Higher cost pressure without the benefits of economies of scale</td>
<td>Potbhare, Syal Korkmaz (2009), Potbhare, Syal, Arif et al. (2009), Collins (1994), Lam et al. (2009, 2010)</td>
</tr>
<tr>
<td>V3</td>
<td>Lack of market demand on green buildings</td>
<td>Lam et al. (2009, 2010), Shi et al. (2013), Chan et al. (2016)</td>
</tr>
<tr>
<td>V4</td>
<td>Limited support from the senior management for GS adoptions</td>
<td>Lam et al. (2009, 2010), Shi et al. (2013), Chan et al. (2016)</td>
</tr>
<tr>
<td>V5</td>
<td>Lack of local R&amp;D institutes and services</td>
<td>Lam et al. (2009, 2010), Shi et al. (2013), Chan et al. (2016)</td>
</tr>
<tr>
<td>V6</td>
<td>Unfamiliarity with green technologies</td>
<td>Lam et al. (2009, 2010), Shi et al. (2013)</td>
</tr>
<tr>
<td>V7</td>
<td>Conflicts with aesthetic issues</td>
<td>Lam et al. (2009, 2010), Ye et al. (2015)</td>
</tr>
<tr>
<td>V8</td>
<td>Poor reliability and quality of specifications</td>
<td>Potbhare, Syal, Korkmaz (2009), Potbhare, Syal, Arif et al. (2009), Meryman</td>
</tr>
<tr>
<td>V9</td>
<td>Incomplete legal framework issues</td>
<td>Potbhare, Syal, Korkmaz (2009), Potbhare, Syal, Arif et al. (2009), Meryman</td>
</tr>
<tr>
<td>V10</td>
<td>Lack of governmental regulations and incentives</td>
<td>Potbhare, Syal, Korkmaz (2009), Potbhare, Syal, Arif et al. (2009), Meryman</td>
</tr>
<tr>
<td>V11</td>
<td>Inadequate green material supply chain</td>
<td>Kibert (2008), Hwang and Tan</td>
</tr>
<tr>
<td>V13</td>
<td>Lack of technology and testing institutes for green specifications</td>
<td>Potbhare, Syal, Korkmaz (2009), Lam et al. (2009, 2010)</td>
</tr>
<tr>
<td>V14</td>
<td>Lack of marketization of specifications</td>
<td>Potbhare, Syal, Korkmaz (2009), Lam et al. (2009, 2010)</td>
</tr>
<tr>
<td>V15</td>
<td>Lack of knowledge on green technology</td>
<td>Lam et al. (2009, 2010), Shi et al. (2013)</td>
</tr>
<tr>
<td>V16</td>
<td>Unwillingness to change the conventional way</td>
<td>Chan et al. (2016), Chen and Chambers (1999), Meryman and Silman (2004)</td>
</tr>
<tr>
<td>V17</td>
<td>Low public awareness of environmental issues</td>
<td>Meryman and Silman (2004), Mollaoglu et al. (2016), Chan et al. (2016)</td>
</tr>
<tr>
<td>V18</td>
<td>Lack of technology innovation</td>
<td>Potbhare, Syal, Korkmaz (2009), Mollaoglu et al. (2016)</td>
</tr>
</tbody>
</table>

Table I. Potential factors for adopting green specifications based on Potbhar et al. (2009) and Lam et al. (2009), etc.
3. Research method

3.1 Research framework
In this paper, the basic research method is shown below. First, the literature review, pilot survey and questionnaires were used to make a survey on the factors that affect the adoption of green specifications. Then, technology and factor analysis were used adopted to analyze the data (Figure 1).

3.2 Data collection

3.2.1 Preliminary factors. Based on the comprehensive literature review’s result above, a questionnaire was designed and evaluated. A pilot study was conducted to refine and revise the questionnaire. Three industry professionals who had experience of more than ten years in this area were invited to comment on the identified variables, considering the background and the market of China’s construction industry, and any factor that could be deleted from or added to the list. The final list of 18 proposed factors hindering the adoption of green specifications formed the main content of the questionnaire design (Table I).

The questionnaire was composed of two parts. To be specific, the first part was designed to collect basic information regarding the respondents’ company type, position, years of experience, and the basic information of their knowledge and experience in green specifications; the second part consisted of the aforementioned 18 preliminary factors. At the end of the questionnaire, a blank box was provided to allow the respondents to add any additional factors, if any. The respondents were asked to evaluate the degree, to which each item was a barrier to green specifications adoption using a five-point Likert scale. The meanings of the points are: 5 represented “strongly agree,” 1 represented “strongly disagree,” and the middle position was neutral.

3.2.2 Data collection. The questionnaire survey was conducted in Mainland China from April 2 to May 27, 2017, and 300 industry professionals in China were randomly selected for the survey through the online questionnaire platform www.sojump.com. At last, 128 valid questionnaires were collected with the rate of 42.6 percent that was consistent with the norm of 20-30 percent in construction management surveys (Hwang et al., 2015). Among the valid questionnaires, 27 percent of the respondents were managers and...
73 percent were engineers and technicians. About the years of construction work experience, 18 percent had more than 20 years of experience in this area; 39 percent had 10 to 20 years of experience; 27 percent had more than 5 to 10 years of experience. Then, the reliability and quality of data are proved.

3.3 Data analysis

The mean score method and factor analysis were used to identify and analyze the barriers that affect the adoption of green specifications by SPSS 10.

3.3.1 MS technology. The mean score method is a simple and effective method of ranking the relative importance, and it has been used in previous project management studies (Chan et al., 2003; Chan and Kumaraswamy, 1995). In this paper, the same method was adopted to analyze the data collected from the questionnaires. The five-point Likert scale (1 = least important, 2 = slightly important, 3 = important, 4 = very important, and 5 = most important) was used to calculate the mean score of each variable, which showed the relative importance level of each variable.

3.3.2 Factor analysis. Factor analysis is a statistical technique which is used to find clusters of the related variables. It can be employed to represent the relationships among sets of many interrelated variables (Norusis, 2008; Huang et al., 2008). It has been widely used in previous studies as Lu et al. (2008) and Wang and Yuan (2011). In this study, factor analysis is conducted to extract the factors and explore the underlying relationships among critical factors.

Before using this method, various tests were indispensable for examining the appropriateness of the factor analysis on factor extraction. In this paper, the Kaiser-Meyer-Olkin (KMO ≥ 0.50; Kaiser, 1974) measure and Bartlett’s sphericity test (p < 0.05; Bartlett, 1954) were conducted. The KMO value is from 0 to 1. If the KMO is close to “1,” the correlation patterns are relatively compact, which means the results are reliable (Field, 2005), while if the KMO is close to “0,” the correlation patterns are diffused, which means it is not appropriate for factor analysis (Norusis, 2008). According to Kaiser (1974), if the KMO value is greater than 0.5, it means the sample is acceptable for factor analysis. Bartlett’s test of sphericity is employed to examine whether a specific correlation matrix is an identity matrix. If the value of the Bartlett’s test of sphericity is large when the associated Sig. is small, the correlation matrix is appropriate for factor analysis (Statistical Package for Social Sciences, 1997).

4. Research results and discussions

4.1 Rank analysis

In this part, the mean score method was adopted to identify and analyze the influence of the variables on the adoption of green specifications in construction projects. The results of mean scores and the ranking for the 18 variables can be seen in Table III.

The results show that the mean values of the variables are from 3.0 for 3.394 to 4.0 for 3.992. The top five critical variables are: lack of governments’ policies and regulation; legal framework issues; higher initial cost; unfamiliarity with green technologies; and bad reliability and quality of specification. The first and second variables as ranked by all respondents, are “the lack of governmental regulations and incentives” (mean = 3.992) and “legal framework issues” (mean = 3.937), which is thus considered as the greatest obstacle inhibiting the adoption of green specifications in China’s construction market. “High initial adoption cost” (mean = 3.921, SD = 0.965) is ranked as the third obstacle. The fourth- and fifth-ranked factors are “unfamiliarity with green technologies” (mean = 3.890) and “bad reliability and quality of specification” (mean = 3.819), respectively.
4.2 Factor analysis
Conducting factor analysis with component analysis and the varimax rotation, 18 variables are divided into five components according to the underlying interrelationships that existed among them. The Bartlett’s test of sphericity ($\chi^2 = 898.398$, df = 153, significance level = 0.000) was significant ($p < 0.05$), and the value of the KMO index (0.897) was above 0.50 (Table I). Therefore, the data in this paper were appropriate and suitable for factor analysis.

From the consequence in Table II, five clusters whose eigenvalues were greater than 1 through principal component analysis were extracted. The total variance cumulatively explained by the four extracted components accounts for 71.392 percent. The results of the matrix can be seen in Table II. Each of the 18 critical factors belonged to only one of the five factors with the factor loading value exceeding 0.50 (Tables II-IV).

---

**Table II.**

<table>
<thead>
<tr>
<th>Kaiser-Meyer-Olkin measure of sampling adequacy</th>
<th>0.897</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bartlett’s test of sphericity</td>
<td></td>
</tr>
<tr>
<td>Approx. $\chi^2$</td>
<td>898.398</td>
</tr>
<tr>
<td>df</td>
<td>153</td>
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<tr>
<td>Sig.</td>
<td>0.000</td>
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</tbody>
</table>

**Table III.**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Total</th>
<th>% of variance</th>
<th>Cumulative %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.956</td>
<td>38.644</td>
<td>38.644</td>
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<tr>
<td>2</td>
<td>1.405</td>
<td>7.805</td>
<td>46.450</td>
</tr>
<tr>
<td>3</td>
<td>1.216</td>
<td>6.755</td>
<td>53.205</td>
</tr>
<tr>
<td>4</td>
<td>1.034</td>
<td>5.747</td>
<td>58.951</td>
</tr>
<tr>
<td>5</td>
<td>1.006</td>
<td>5.590</td>
<td>64.541</td>
</tr>
</tbody>
</table>

**Table IV.**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean value</th>
<th>SD</th>
<th>Rank</th>
<th>Factor, variable groupings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>V13</td>
<td>3.661</td>
<td>0.986</td>
<td>9</td>
<td>0.723</td>
</tr>
<tr>
<td>V8</td>
<td>3.819</td>
<td>0.987</td>
<td>5</td>
<td>0.701</td>
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<tr>
<td>V18</td>
<td>3.693</td>
<td>0.913</td>
<td>7</td>
<td>0.683</td>
</tr>
<tr>
<td>V6</td>
<td>3.890</td>
<td>1.018</td>
<td>4</td>
<td>0.651</td>
</tr>
<tr>
<td>V7</td>
<td>3.638</td>
<td>0.879</td>
<td>10</td>
<td>0.628</td>
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<tr>
<td>V5</td>
<td>3.661</td>
<td>1.071</td>
<td>8</td>
<td>0.559</td>
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<tr>
<td>V16</td>
<td>3.394</td>
<td>1.070</td>
<td>18</td>
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<tr>
<td>V17</td>
<td>3.409</td>
<td>0.979</td>
<td>16</td>
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<tr>
<td>V15</td>
<td>3.394</td>
<td>0.910</td>
<td>17</td>
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<tr>
<td>V4</td>
<td>3.591</td>
<td>0.965</td>
<td>12</td>
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<td>V10</td>
<td>3.937</td>
<td>1.052</td>
<td>2</td>
<td>0.809</td>
</tr>
<tr>
<td>V9</td>
<td>3.992</td>
<td>0.988</td>
<td>1</td>
<td>0.797</td>
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<tr>
<td>V12</td>
<td>3.591</td>
<td>0.770</td>
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<td>0.669</td>
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<tr>
<td>V11</td>
<td>3.591</td>
<td>0.770</td>
<td>14</td>
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<td>V3</td>
<td>3.787</td>
<td>0.914</td>
<td>6</td>
<td>0.607</td>
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<tr>
<td>V14</td>
<td>3.606</td>
<td>1.085</td>
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<td>0.546</td>
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<tr>
<td>V2</td>
<td>3.543</td>
<td>0.990</td>
<td>15</td>
<td>0.862</td>
</tr>
<tr>
<td>V1</td>
<td>3.921</td>
<td>0.730</td>
<td>3</td>
<td>0.723</td>
</tr>
</tbody>
</table>

Results of factor analysis for factor matrix after varimax rotation
5. Findings and discussion

5.1 Factor 1: green technology

The “green technology” factor consists of six critical variables: lack of local R&D institutes and services; lack of technology and testing institutes for green specifications; conflicts with aesthetic issues; poor reliability and quality issues of specification; unfamiliarity with green technologies; and lack of technology innovation. The six critical variables under this component focus on the green technology when green specifications adoption. This component accounts for 38.64 percent of the total variance explained among all of the critical variables (Table III).

The green specifications in China have just been issued only a few years ago. Now, there is no systematic technology institute for green specifications research and revision. The general green specifications are generally recommended specifications; they should be developed when they are in different provinces. However, there are no local institutes that focused on the research work of local specifications. The specifications need to be considered in life cycle sight and differ according to the characteristics of different climatic regions and different types of buildings. Besides, in China, there are no special technologies and testing institutes to examine the practice of green specifications, and detail technical specifications for examining green buildings are lacking.

The aesthetic appearance of a building may conflict with green specification adoption. Clients often focused on the aesthetic appearance, but the adoption of green specifications can cause the degradation of aesthetic appearance (Pierce and Daniel, 2000). For example, as to the installation of solar panels, architects have to spend time on how to integrate it with the materials on the façade or the house roof (Shi et al., 2013).

Although China has achieved obvious progress in specifications and R&D work for green buildings in recent years, and many problems still exist. The promulgation of legislation and mandatory green specifications and regulations that set boundaries for market activities is a government function that is crucial for ensuring that green specifications are widely accepted in the market (Potbhare et al., 2009). However, in China, governments have issued a series of green specifications, but the implementation of these policies is either inadequate or absent. Most of the green specifications are voluntary, while mandatory green codes and regulations are lacking, causing individuals to eschew the adoption of green specifications.

Eisenberg et al. (2002) stated that insufficient knowledge and unfamiliarity with green materials and products related to green technology are certain barriers to green specification adoption. When compared with the conventional technology, green technology is usually complicated (Tagaza and Wilson, 2004). Unfamiliarity with green technology, lack of the knowledge of the green specifications may affect the adoption behavior (Zhang et al., 2011).

Another barrier is the lack of technology innovation, mainly because of the shortage of R&D research investment in China’s building sector. In order to achieve sustainable development for the construction area, it is important to make innovation for construction technology (Vanegas and Pearce, 1997). However, in China, the research grant for the building area is only 0.4 to 0.6 percent in the GDP of the total construction area.

5.2 Factor 2: awareness and attitude

Four variables (including limited support from the senior management for GS adoptions; lack of knowledge on green building specifications; unwillingness to change the conventional way; and low public awareness of environmental issues) should be grouped into this underlying factor for the successful adoption of green specifications owing to the strong correlations inside. This factor should be the most important one in terms of the percentage of covariance among variables.
Support from the top management directly affects the adoption of green specifications (Meryman and Silman, 2004). The employees can accept and adopt green building specifications better if the senior management want and commit to environmental issues (Ball, 2002).

The lack of knowledge on adoption of green specifications is a significant barrier that prevents the adoption of green specifications. Due to the uncertain performance, a construction enterprise can reject to adopt green specifications as the adoption of green specifications may result in extra costs.

Another technical barrier is the unwillingness to change the conventional way, as noticed by Meryman and Silman (2004). This is the same as the findings of Chen and Chambers (1999). The traditional ideas are still deeply rooted in the construction areas in China. Most construction enterprises always carry on their construction work depending on their experience and unwilling to change, let alone adopt the new green specifications.

The public environmental awareness is also closely related to the adoption of green specifications. In China, although people are recognized and affected by the environmental issues, majority of them attribute the problem to the responsibility of government involvement or companies' participation. In order to improve the awareness of the environment, the knowledge and cognition on benefits of green specifications adoption of all parties, including policy makers, owners, designers, construction personnel and the public, should be further enhanced in China (Shi et al., 2013).

5.3 Factor 3: policies and regulations

This factor consists of two critical variables, accounting for 8.01 percent of the total variance explained among all critical factors. Through the understanding of the indices' meaning, the factor was the theme without difficulties as policy and regulation barriers, including: lack of legal framework for green specifications; and lack of governmental regulations and incentives for green specifications adoption (Table II).

Having an efficient legal framework and procedure is the basic guarantee for the successful adoption of green specifications. The effective legal framework involves related policies, regulations, codes and specifications to guide all stakeholders including government officials, designers, contractors and developers to adopt green specifications well during the green construction process. In China, the basically necessary legal framework for supporting the adoption of green specifications is inadequate as China has a short time for its own green building specifications (Shi et al., 2013).

The lack of government policies and incentives for green specifications adoption is identified as the foremost barrier in the research result. Currently, the Chinese Government has issued a series of green specifications on building development, focusing on structural quality, energy saving, and green materials. However, most of them are voluntary policies which cause the failure of their execution. Consequently, enterprises fail to adopt green specifications, and government departments also fail to supervise the entire chain.

In order to overcome this obstacle, policy guidance from the government department is a critical method. The government can provide effective financial incentive measures, such as tax incentives, financial discounts, deficit subsidies and pre-tax loans for green specifications adoption. Construction companies benefit from the policies and will be more willing to adopt green specifications. Besides, some of the specifications can be formulated as mandatory environmental requirements, such as government green procurement policies and mandatory requirements in the public-sector projects. Environmental considerations can be integrated with the purchase policies like environmental or green procurement policies (Russel, 1998). Government green procurement policies can give practice to enterprises for green specifications adoption. There are many countries in the world that have green public procurement (Bouwer et al., 2006; Kippo-Edlund et al., 2005;
Ochoa and Erdmenger, 2003). Currently, China has a high proportion of the public sector among the construction industry. Mandatory requirements in the public-sector projects provide practice examples and lead the private sector to adoption green specifications. Reasonable incentives can encourage the market to pursue GS. Since 2001, the Buildings Department of Hong Kong has implemented incentive schemes in the building sector to promote the adoption of green technologies. Under these schemes, the gross floor area exemption is granted to developers of buildings with green features (Mao et al., 2015). Thus, in Mainland China, more incentives are required, not only to develop green specifications, but to offset the additional costs involved in it as well.

5.4 Factor 4: market
This factor contains four critical variables: lack of market demand on green buildings; inadequate green material supply chain; lack of benchmarking system; and lack of marketization of specifications. This cluster is responsible for 6.53 percent of the total variance explained among all critical factors (Table II).

Market demand also affects the adoption of green specifications. With the high housing price in China, consumers pay more attention to the buying cost and the quality, rather than the construction method or the process of their buildings. Lack of market demand for green buildings causes the failure of green building specifications.

The inadequate green material supply chain is another challenge for green building specifications. As China’s green technology and materials market is not mature now, green technology and materials are expensive when compared with the conventional materials and technology. Although stakeholders want to carry out green specifications, they have risk of getting and using green materials. The uncertainty of supplies and information is a significant barrier against green specifications adoption (Love et al., 2002; Shi et al., 2012), and it can cause a delay for construction work. Thus, inadequate green material supply chain hinders the adoption of green specifications.

China has just established its green building specifications system for a few years. There are few benchmarking examples of construction projects with green specifications adoption in China (Lee and Chen, 2008). Besides, in China, there is no relative database for green buildings, which causes the situation that the construction enterprises have no references for green specifications adoption behavior.

There lacks marketization for specifications. Take UK for example. BSI plays an important role in the adoption of green specifications are in a state of marketization. However, in China, the government department with the total control power of the specifications sets and reformulates standards that is the SQDOHURD (Standard Research Institute of Housing and Urban-Rural Development of the People’s Republic of China). A non-governmental organization plays a limited role in developing and embedding standards in China, which has led to the disconnection between market demand and green specifications. In addition, it lowers the green innovation of construction enterprises. Now, the Chinese Government has changed the standard system step by step. It intends to give more freedom to the non-governmental organization for issued standards.

5.5 Factor 5: economics
This factor refers to “economics,” and contains two critical variables: higher adoption cost; and higher cost pressure without the benefits of economies of scale. Furthermore, the two variables account for 7.31 percent of the total variance explained among all critical factors (Table II). In China, cost has been considered as one of the major and sensitive obstacles that hinders green specifications adoption, and it is consistent with previous studies’ results (Meryman and Silman, 2004; Ofori and Kien, 2004; Liu et al., 2012).
From studies, it has been found that the higher initial adoption cost is mainly associated with the considerations for decisions of green specifications adoption (Meryman and Silman, 2004). Extra cost of green specifications is the prime obstacle (Ofori and Kien, 2004). The adoption of green specifications should adopt green techniques and materials, such as equipment for water or energy savings and high-performance insulation protection (Hwang and Tan, 2010). Consequently, all of these can cause the increase of the extra initial cost. In this case, most stakeholders consider the extra cost as a considerable loss of their profits. Liu (2012) argued that the control of cost is one of the biggest challenges for the stakeholders to adopt green specifications. Zhang et al. (2011) proved that the cost of using green materials will be from 3 to 4 percent when compared with using conventional construction materials.

The higher extra cost with the lack of economies of scale is also considered as a pressure for green specification adoption. Lack of the economic scale due to the insufficient quantity demand means an increase in cost per unit as fewer units are produced. Currently, to achieve the expected economies of scale for green specifications in China, the government support is necessary. In China, the stakeholders will not be able to adopt green specifications, as they cannot receive direct and quick monetary profits but the higher adoption cost. Therefore, researches on how to enhance the market competitiveness for green specifications adoption and how to assist the promotion of green specifications adoption are imminently necessary.

Shi recommended the use of life cycle approach for the sustainable construction in China. Lam suggested that further studies should be performed on possible savings in life cycle cost and the possible costs of environmental remediation for green specifications. Previous studies encouraged the adoption of green specifications. Therefore, in order to relieve the adoption cost barriers faced by stakeholders, more successful benchmarking practices should be shown on the economics scale benefits of green specifications in China. Besides, the effective lead and support from the senior management can directly affect the adoption of green specifications (Meryman and Silman, 2004).

Shen et al. (2010) pointed out that the government’s guidance and support is the key to green specifications for construction enterprises. Guide and support can lead and increase the demand of the green building market. It can also give financial support for the development of green technology. With the demand increase and green technology, those who adopt green specifications can be good practice for other construction enterprises. Cost of adoption green specifications can been offset by scale economy. The awareness and attitude of different stakeholders can be enhanced. Nowadays, the Chinese Government now has considered to mandatorily adopt green specifications in some pilot cities.

6. Conclusions and implications
The construction industry has consumed more global resources. Sustainable construction is a useful way for resource saving and sustainable development. Green specifications are the basic guarantee and reference for sustainable construction. However, in China, green building specifications has not been well used which hindered the process of sustainable construction. This study presents a comprehensive explanation of the barriers that hinder the adoption of green building specifications in China. Based on literature review, 18 critical barriers that affect the adoption of green building specifications in China are initially identified by conducting the questionnaire survey. In order to understand the interrelationship among factors better and clearly, this paper uses factor analysis and rank technique method for further analysis. The study has identified that government-related factors are the foremost factors for the adoption of green specifications in China. By making factor analysis, the basic 18 critical variables are categorized into five factors: green technology and techniques; awareness and attitude; governments’ policies and regulations; market demand; and cost. The results also indicate
that the most dominant one of the five clusters pertains to regulations and policies. The findings tend to highlight the factors that affect the adoption of green specifications in China, and give policymakers advice to better implement green specifications in China. Results show that solutions to overcome the barriers in China mainly depend on the government. The results can also give other developing countries reference for better adoption of green specifications.

The research result is important as it focuses on the adoption of green building specifications in China at a time when the country experiences huge development in the construction environment allied to huge requirements in sustainable technology. The findings in this paper have shown some insights for the recognition of factors in the adoption of green building specifications in China, and reliable guides and appropriate decisions for green building specifications adoption and environment improvement are provided for China’s construction industry, which may contribute to the enhancement of green building specifications and provide China’s construction industry with a decent environment. In future research, the factors that affect the adoption and implementation of green building specifications in other countries and on other aspects should be explored.

References
Green building specifications in China


Further reading

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Failure is an option: an innovative engineering curriculum

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Division of Natural and Built Environment, University of Abertay Dundee, Dundee, UK

Abstract

Purpose – Advancements and innovation in engineering design are based on learning from previous failures but students are encouraged to “succeed” first time and hence can avoid learning from failure in practice. The purpose of this paper is to design and evaluate a curriculum to help engineering design students to learn from failure.

Design/methodology/approach – A new curriculum design provided a case study for evaluating the effects of incorporating learning from failure within a civil engineering course. An analysis of the changes in course output was undertaken in relation to graduate destination data covering 2006 to 2016 and student satisfaction from 2012 to 2017 and a number of challenges and solutions for curriculum designers were identified.

Findings – The design and delivery of an innovative curriculum, within typical constraints, can provide opportunities for students to develop resilience to failure as an integral part of their learning in order to think creatively and develop novel engineering solutions. The key issues identified were: the selection of appropriate teaching methods, creating an environment for exploratory learning, group and team assessments with competitive elements where practicable and providing students with many different pedagogical approaches to produce a quality learning experience.

Originality/value – This case study demonstrates how to design and implement an innovative curriculum that can produce positive benefits of learning from failure. This model can be applied to other disciplines such as building surveying and construction management. This approach underpins the development of skills necessary in the educational experience to develop as a professional building pathologist.

Keywords Innovation, Learning, Failure, Curriculum development, Engineering design

Paper type Case study

1. Introduction

Engineering design is a goal-driven, problem-solving discipline that seeks to use technologies and materials to satisfy user requirements, taking into account applied constraints. The designer seeks to optimise outcomes within the available solution space, which drives a search for innovative and creative solutions to a combination of challenges that range from end-user demands to limitations of materials or application of techniques in new building design. In the search for innovation, some proposed solutions will inevitably fail to provide the desired outcomes (Sawyer, 2011; Syed, 2015). These failures can be an important feature of the innovation process, driving greater understanding, which can then be embedded into the design of future solutions. In this context, it is important that engineers do not simply discard failures but carry out rigorous analysis and evaluation so that the embedded knowledge is transferred to other engineers and other projects. Learning from failure should thus be an integral feature of an effective engineering design curriculum that trains graduates to learn from failure.

Within the context of the paper the use of the term “failure” is interpreted as a universal feature of the engineering design process, which, if used correctly, has educational benefits (Sitkin, 1992; Petroski, 2016). Engineering students should be encouraged to attempt innovative and potentially risky solutions, but this approach can be inhibited by constraints of the curriculum. This paper examines the literature on the nature of innovation and its links to the engineering design process. The link between learning from failure within engineering design, development and implementation, and the implications for students and course providers is discussed in the context of key areas of curriculum design that can be enhanced...
by learning from failure. A case study is then presented of a civil engineering course where teaching, learning and assessment principles were adapted to enhance learning from failure whereby design innovation and risk taking were encouraged. The paper reflects on the outcomes that have been recorded since introduction of the curriculum including monitoring of student satisfaction and destinations. The case study provides insights for other disciplines, such as surveying and construction management indicating the benefits of embedding the practice of learning from failure within a curriculum.

2. Literature review

2.1 Innovation in engineering design

The definition of innovation is ambiguous with Baregheh et al. (2009) suggesting upwards of 40 definitions currently in use, from which this paper has adopted:

Innovation is the multi-stage process whereby organizations transform ideas into new/improved products, service or processes, in order to advance, compete and differentiate themselves successfully in their marketplace.

The engineering design process is a parallel process involving both the feedforward and feedback of structured information relating to the product development (Bullinger and Warschat, 2012), resulting in a cyclical model of engineering development. The engineering design process must balance activities between those of the design theorist and the design pragmatist. Innovations in engineering design can evolve incrementally over time through a process of experiment and evaluation, in which an understanding of the nature of failure plays an important part (Petroski, 1998). Innovations emerge over time as individuals gather information about need, requirements, problems, potential outcomes and solutions along with consideration of the target market. Engineering design failures occur on a reasonably regular basis, and are traceable to a number of causes despite all efforts to prevent it being the case. There is a need for professionals in disciplines that inform construction design, such as building pathology, to build up the skills and attributes to analyse failure and identify the underlying causes, an important part of informing the innovation process.

2.2 Influence of innovation on curriculum design (how to learn from failure)

For the purposes of this paper a curriculum is considered to be the process of learning for life within a framework that determines the context for transforming information into knowledge through the medium of a range of activities (Biesta, 2014). The curriculum needs to develop transformational learning to enable students to engage with risk taking and creating innovative solutions, whilst understanding the iterative nature of learning from failure and accepting failure as an integral part of the learning process (Limoncelli et al., 2012). A key aspect of innovation is the ability to identify and develop concepts that have originated in other ways and from other areas and to recognise that they have a potential application in relation to the specific problem for which a solution is being sought (Bullinger and Warschat, 2012). This implies an open-minded approach in which no concepts or ideas are rejected simply because they do not fit a pre-conceived model of a solution (Chesbrough et al., 2006). This requires individuals to develop skills, tools and professional attributes to implement the solution. For the course designer this implies a need to establish a sound technical base while embedding an understanding of risk and failure within innovation and providing the tools to be able to analyse failures to establish cause. Over time a number of design support tools have been developed (Chakrabarti, 2013) that can support decision making in design. The engineering designer must be able to use these tools effectively in the reduction of the initial solution space, containing all viable solutions, taking into account relevant external factors.
The curriculum determines the skills, knowledge and professional attributes a graduate will develop and how prepared they are for employment (Knight and Yorke, 2002). Therefore, in relation to engineering design and innovation, where there are national standards overseen by professional bodies what scope is there to create a curriculum that embeds learning from failure within the teaching, learning and assessment practice and what is the impact of doing so? In comparing the performance of experienced vs novice scientists, Feist (2008) noted that:

- expert scientists are more willing to modify or discard hypotheses than novices;
- experts demonstrate more cognitive complexity when they discuss their domain;
- novices solve problems and evaluate evidence based on more common sense representations; experts form abstract representations;
- experts use chunking and mode-linked representations of large quantities of domain knowledge;
- experts work forward from the information given; novices work backwards from a possible solution; and
- experts are more likely to discover useful analogies.

This suggests that the behaviour of the expert is tempered by experience, including that of failure, and that the course designer needs to consider the underlying experience of the students (Limoncelli et al., 2012).

Froyd et al. (2012) identified five major developments that have taken place in engineering education over the previous 100 years:

(1) a transition from hands-on and practical experience to engineering science and analysis;
(2) a transition to outcomes-based education and accreditation;
(3) an increasing emphasis on the role and contribution of engineering design;
(4) the application of education, learning and social and behavioural sciences research; and
(5) the integration of information, computational and communications technologies within education.

In examining the context, the work of Froyd et al. (2012) indicates that there is a transition from hands-on and practical experience that Feist (2008) indicates is an essential element of knowledge creation. The skill of the curriculum designer is to achieve an appropriate balance between the underpinning science and analysis with learning from experience if the curriculum is to align with current expectations of those influencing accreditation and quality reviews.

2.3 Challenges in curriculum design

In the UK, the National Student Survey (NSS), the Teaching Excellence Framework and the Higher Education Academy are influencing the increasing use and reporting of innovative approaches to delivering, and assessing students (Medland, 2016) requiring academics to act as the catalyst and enablers for change (Louvel, 2013). Quality assurance processes, where metrics drive the assessment of quality, can lead to situations where the holistic student experience is not recognised (Teelken and Lomas, 2009). Students have considerable influence over teaching and assessment practice where satisfaction is taken as a proxy for quality of the student experience with the consequence that students get the
learning experience they want and not necessarily what they need (Douglas et al., 2006). Students will go through a range of challenging emotional experiences during their learning, for example anxiety or anger, particularly if they have not “succeeded”. These emotions can be a source of negative student feedback where a positive attitude towards building personal resilience to failure is not an embedded part of the learning process (Martin, 2002). When combined with robust reflection, learning from failures can instead result in interest, enjoyment and pride in tasks (Tulis and Ainley, 2011).

The typical measure of student success is through grades; high grades are derived from the provision of “correct” answers. Within this context the low-risk option for students is to practice for assessments and to find out what is deemed to be a correct answer (March, 1996). Academics need to have the skills to adapt to the increasing number of pedagogies (Dede, 2007) but under pressure to meet targets the low-risk option is to rely on established teaching methods and assessments that promote student satisfaction over creativity and open-ended complex problem solving (Binns, 2016; Voss et al., 2007). The conditions for innovative pedagogy that develop the academic resilience, critical thinking and problem solving skills of students need to be examined for their effective contributions to the iterative process of learning from failure. The curriculum also needs to ensure that the learning experience within higher education is constructively aligned with the expectations of industry and professional bodies (Holdsworth and Hegarty, 2016), including issues of:

- how students learn – in particular interpretation of complex diagrams and taking notes;
- learning how to work effectively in groups;
- learning beyond the boundaries of any single discipline;
- learning how to interpret behaviours and to distinguish between wants and needs; and
- developing effective communication skills using appropriate technology, maintaining the desire to keep up with technology developments for securely shared information.

2.4 Recommendations for incorporating learning from failure into curriculum design

The transition from practical experience to analysis, identified by Froyd et al. (2012), gives rise to the need to examine whether this results in a gap in student knowledge. In examining the factors that would influence curriculum design and delivery the following were also considered:

1. the establishment of a sound technical base including the understanding that engineering design is an interdisciplinary area of study involving a range of additional non-engineering skills and expertise (Dym et al., 2005);
2. provision of support for individuals in developing personal, presentational, communication and listening skills (Moseley et al., 2005);
3. support for individuals in developing note taking and diagramming skills to articulate innovation with content to provide the skills, tools and resources required for its implementation (Salter and Gann, 2003);
4. concept development and the creation of opportunities for the cross-fertilisation of ideas and expose individuals to different means of thinking about, and solving, problems;
5. creation of opportunities for group and team working with an emphasis on design and innovation with the focus on collaboration (Najdanovic-Visak, 2017);
6. encouraging innovative approaches rather than conservative ones (O’Connor et al., 2008).
(7) embedding an understanding of risk and failure within innovation and providing the tools to be able to analyse failures to establish cause;
(8) developing an understanding of the user, their aims and goals (Joshi et al., 2012);
(9) access to, and the sharing of, information increasingly structured around electronic means;
(10) legislation, for instance regarding intellectual property, and its impact on the design process;
(11) grading schemes for projects involving collaboration with students that acknowledges different skills (Gavin, 2011); and
(12) quality mechanisms and their operation (Tannock and Burge, 1994).

These issues can be grouped in relation to curriculum properties shown in Table I. The starting point for the implementation of all of the above is the nature of a curriculum. The key features of teaching, learning and assessment are discussed in further detail in the sections that follow.

2.4.1 Teaching – what to teach. Study skills are essential preliminary core skills for learning including note taking, report writing, essay writing critical thinking, etc. A coherent approach to embedding these skills within the delivery establishes the necessary foundation for knowledge development and deep learning for student success (Felder et al., 1998). The concept of establishing cause and effect in the curriculum design aids the process of prioritising the content, when and how it is delivered. Students cannot write professionally using appropriate language from an engineering design perspective until they know how to write professionally in general. They cannot write anything meaningful for content until they have the ability to think critically and articulate their thoughts. They cannot think critically until they have the knowledge to criticise and evaluate the information. They cannot evaluate information until they have established how to retrieve relevant information and so on. These elements must be at the core of the curriculum.

The course designer is expected to include the concepts of engineering design while providing access to the necessary tools along with an understanding of their use, operational implications and limitations whilst ensuring students are ultimately able to (Dym et al., 2005):

- manage the ambiguities that inevitably result in the concept stages of the design process, requiring a combination of divergent thinking, ability to consider multiple potential outcomes and fact-based convergent thinking;

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Technical content</th>
<th>Knowledge development</th>
<th>Technical skills development</th>
<th>Academic skills development</th>
<th>Pedagogy</th>
<th>Professional attributes</th>
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Table I. Distribution of structural issues in relation to curriculum properties
place ideas within the context of the desired outcomes and of the associated systems concepts and dynamics;

- manage the uncertainty associated with the engineering design process, particularly in the early stages of concept development that is associated with incomplete and imperfect models, incomplete information and potentially ambiguous objectives;

- have an ability to estimate outcomes based on the identification of the key parameters driving the design; and

- communicate between the members of a design team using a variety of forms including verbal, diagrammatic mathematical models and parametric or numerical data.

The subject content and means of delivery are then open to various internal and external organisational influences in relation to identifying and implementing effective means for achieving the objectives of the curriculum (Anderson and Rogan, 2011). For example, the introduction of Building Information Modelling has changed the process of procuring, constructing and operating built assets, which is increasingly dependent upon collaborative working. Whilst team working has always been an essential part of delivering projects, the nature of integration is now essential as more specialisms are included within the team across the project delivery and operation. The cross-fertilisation of ideas is crucial to innovation and is often formed from informal interactions in environments with very low cultural barriers to communication. This requires the course designer to enable individuals to develop personal, presentational and communication skills, including the ability to listen to others, indicating a need to create numerous opportunities for collaborative working where teams can share ideas and individuals engage with different approaches to thinking about, and solving, problems.

2.4.2 Learning – how to teach. There are a number of methods that can be used to provide a transformational learning experience that enables students to engage with risk taking and the creation of innovative solutions including:

- problem-based learning (Davies, 2013; Dym et al., 2005), including analysing and learning through failure (Cavalline and Delatte, 2015);

- research-based learning (Gosper and Ilfenthaler, 2014);

- “flipped classroom” (Potter and Jacobson, 2014);

- assessment practice (Schkoda et al., 2013);

- work-based learning (Hartmann and Light, 2010); and

- digital learning technologies (Salmon, 2005).

A wide range of teaching approaches at the earlier stages of a student’s learning experience exposes them to a diverse range of learning opportunities and helps them to develop life-long learning skills (Sunthonkanokpong, 2011). Key issues include ensuring appropriate balance between individual learning, collaborative learning, face-to-face and on-line teaching (Paechter and Maier, 2010). The successful use of technology for teaching delivery depends on a number of factors including the availability of resources and sufficient expertise of the designer to optimise the benefits of each technology effectively (Blin and Munro, 2008).

“Deep learning” requires the teaching team to implement the delivery methods with care to avoid students taking a strategic or surface learning approach to their studies and to ensure that the course context does not over-emphasise problem-solving procedures over conceptual understanding (Case and Marshall, 2004). The constructivist pedagogy is based on the theory that learners develop new understanding through taking responsibility for the
process of building on and transforming their existing knowledge. Pedagogical methods that can be considered to be constructivist can be broadly described as inquiry based for which there is evidence that there is a contribution towards deep learning including problem-based learning, case studies and experiential teaching methods (Piercy et al., 2012).

2.4.3 Assessment. The appropriate assessment methodology that encourages learning from failure should recognise the learning process for individuals (Hughes and Jones, 2011). The issues that assessment practice needs to address include:

- designing holistic assessments that combine technical knowledge and soft skills for each individual whilst working collaboratively; and
- moving towards open-ended, problem-based learning teaching methods that encourage and recognise learning through student reflection on the process rather than a specific “correct” solution.

Formative assessment provides opportunities for learning from failure (Cauley and McMillan, 2010). The skill for the curriculum designer is in getting the appropriate balance between formative and summative assessment that provides for learning through failure with sufficient motivation of students to engage with all the formative assessments (Harlen and James, 1997).

The type of collaborative assessments that encourages highly motivated and creative approaches includes project simulations and involvement in competitions. Assessment of soft skills such as negotiation or conflict resolution within a collaborative assessment can become a source for negative student feedback if the processes of learning and personal development are not adequately recognised. Grading requires acknowledgement of the learning associated with the process of problem solving in addition to the final solution (Bacon et al., 1999).

Quality assurance and enhancement can assist in identifying, reducing or removing barriers to implementing curriculum change. Quality reviews are shifting focus towards the learner and the learning experience, with more attention given to internal processes and internal motivators based on a research-informed, evidence-based and enhancement-led approach (Chung and Law, 2010). In formulating metrics, it is prudent to take note of Strathern’s (1997) restatement of Goodhart’s Law, namely that “when a measure becomes a target, it ceases to be a good measure! The students themselves are the sole judges of whether or not satisfaction has been achieved. It follows that irrespective of flaws or complexity of any curriculum design and delivery what is transparent and measured is “satisfaction”. How students interpret this, contextualise and score is irrelevant. The results of student feedback will drive curriculum change with the consequence that students will get what “satisfies” them, but what may be required to learn may not always be what is found to be “satisfying” (Wu et al., 2010).

3. Study methodology
The purpose of the study was to design and evaluate a curriculum that included a change of content and delivery to focus more on developing the skills required for engineering design students to learn from failure. Based on principles discussed in Section 2, a course was redesigned to incorporate learning from failure more effectively in the curriculum.

Reigeluth and Frick (1999) examined research methods to assess their suitability for creating and improving instructional design theories and recommended “formative research” as a version of action research to improve design theory for designing instructional practices or processes. The process involves researchers and practitioners collaborating in the design, implementation and analysis of changes in practice. Formative evaluation is a methodology for improving curricula through answering questions such as...
“What is working?”, “What needs to be improved?” and “How can it be improved?” to develop and test design theory on curriculum development (Reigeluth and Frick, 1999). The underlying logic of formative research is that any weaknesses that are found in the application of the theory may reflect weaknesses in that theory, and any improvements identified for the application may reflect ways to improve the theory. Formative research follows a case study approach and for this research, a holistic single case is appropriate when examining how to improve a design theory (Baxter and Jack, 2008).

The case study adopted involved the redesign of a four-year civil engineering undergraduate degree from 2006/2007 to 2016/2017 with 328 students from the new curriculum graduating from 2012/2013 onwards. Analysis of the impact of curriculum change was undertaken and data were examined in relation to identifying outcomes for employability (Graduate destination data) and student satisfaction (NSS survey data). Qualitative data from student feedback on module delivery were reviewed to examine any issues indicating student development or inhibition of creative and innovative engineering design solutions.

4. Case study

The course team had the opportunity to revise a BSc (Hons) civil engineering course as a result of re-accreditation. At the same time recruitment was relatively low and there were insufficient graduates to achieve minimum numbers for specific course data on student satisfaction. The team therefore planned to design what was considered to be a new, exciting course and take an innovative approach to the curriculum design and delivery.

4.1 Curriculum design

The following sections describe the case study curriculum applied, and key considerations for curriculum designers at each stage of delivery. The stakeholders involved in the curriculum design included staff, students and members of the Industrial Liaison Panel (ILP), providing an industry perspective. The phasing out of a BSc (Hons) course in civil engineering and the implementation of a new BEng/MEng civil engineering gave rise to the opportunity to design and implement a new curriculum, which consisted of six key elements:

(1) technical content;
(2) knowledge development;
(3) technical skills development;
(4) professional attributes;
(5) pedagogy; and
(6) academic skills development.

An outline of the curriculum applied is provided in Table II.

Structuring and delivering the content required consideration of the appropriate order of delivery to ensure that the skills are developed and applied as the basis of sound knowledge development. The core delivery team has educational qualifications and professional recognition for their teaching. Pedagogies that are based on knowledge building focus on working together, discourse and the shared goal of idea improvement (Ellis et al., 2010), which are embedded in the curriculum, and more evident within the work-based learning opportunities.

In each year, learning from failure was embedded into the course in the following areas:

- Year 1 – core study skills, learning from feedback; structures design/testing; collaborative project to develop softer skills and integrate knowledge.
- Year 2 – structure design/geotechnics; feedback week activities (sandwich placement); internal competition to design and constructing a scale structure.
4.2 Evaluation of curriculum redesign

A range of different tools is available to examine the impact of curriculum change, including observation, student feedback at module and course level and quality assurance processes.
The NSS is a measure of student satisfaction at fourth year and can provide an indication as to how students’ perception of the quality of the course is changing over time, as well as provide a comparative measure relative to similar courses across the sector. Due to low student numbers in earlier years, the first year where sufficient numbers of fourth year students responding to the NSS survey was 2012. Figure 1 presents results for key indicators for the NSS survey from 2012 to 2017 for the case study civil engineering course at the institution presented in this study (Higher Education Funding Council for England, 2017). During the period of 2012-2014, overall student satisfaction remains relatively stagnant, falling during a period of staff shortage, and staff turnover in 2014. From 2015, overall student satisfaction has steadily increased, to 100 per cent overall satisfaction in 2017. A comparison of results in 2015 to sector averages found that the course scored significantly better than sector averages for civil engineering in teaching, assessment and feedback, academic support, organisation and management, personal development and overall satisfaction. While it is not possible to compare NSS results prior to curriculum change, these data provide some evidence that the new curriculum is meeting student needs.

Beyond student satisfaction, measures of graduate destinations can assist in evaluating the effectiveness of the course for preparing students for employment. The graduate destination data for the student cohorts in the case study course are presented in Figure 2 covering a ten-year period and 328 graduates from 2006 to 2016. The data presented in the
The graduates of the revised curriculum are more likely to respond to requests for information about their next career stages, reducing the “unknown” responses indicating a greater engagement with their learning experience and willingness to provide feedback for future developments. The number of students obtaining employment in their discipline is markedly higher, as is the number seeking further study to complete their education for a chartered engineer career path.

Additional evidence on whether students responded positively to the incorporation of learning from failure in the curriculum can be found in student confidence to engage in more risk-taking behaviours. In the case study civil engineering programme, year 2 undergraduate students have benefited from learning through an internal competition to design and construct a scale structure. In 2016/2017, the entire year entered a national competition of a similar nature sponsored by the Institution of Structural Engineers and one team went on to beat other university teams that included students at higher levels, including MSc students. Module surveys provide direct student feedback across various modules and help to identify key areas that students are deriving value from the course. Across module surveys, multiple students indicate that the methods of course delivery make the subjects interesting. For example, one student commented:

The way the course has been presented to students is great, the method of teaching is excellent and the course content is interesting (response to 2017/2018 module survey).

Students also indicated that they enjoy learning from industry experts, providing a contextualisation of real-world problems. For example, students commented:

[...] sharing his past experiences in the Civil Engineering industry [...] is great to learn from (response to 2016/2017 module survey).

[...] bringing real companies to come and speak to us, so we can hear other people experiences (response to 2016/2017 module survey).

Students also indicate that the course is preparing them for the world of work. For example, students commented:

[...] helps to give an understanding of the industry we are about to embark upon (response to 2017/2018 module survey).

[...] feedback from last year’s placements, really helped in terms of forward thinking for short and long term goals (response to 2017/2018 module survey).

Together, the analysis of overall student satisfaction, graduate destinations and direct student feedback implies some positive implications of the curriculum redesign. In addition, the course has received accreditation by the Joint Board of Moderators (JBM), who commented favourably upon the inclusion of an ILP in steering the course content and delivery and the influence of industry members in supporting course developments.

Notwithstanding the positive results of the implementation, there are areas that have been identified where improvements can be made. For example, the JBM indicated that the final year MEng group project could be enhanced if the team could provide students with some design office space using one-day design studio sessions involving local practising architects or engineers as appropriate. This could enhance the opportunity for students to learn from industry practitioners further.
5. Discussion and conclusions
The civil engineering course curriculum appears to have successfully embedded learning from failure within the student experience. Positive changes were identified and a number of challenges addressed that can be applied to any surveying or construction management course:

(1) The selection and application of appropriate teaching, learning and assessment methods is critical. To develop professional skills such as persistence, dealing with uncertainty, critical thinking and analytical thinking within a multi-disciplinary context, the curriculum has to create learning environments within which students may experience failure and learn from exploratory learning. In our case study, incremental developments continue as the course is delivered, informed by feedback from staff, students, the ILP and the JBM by placing the focus on the learner, in the same context identified by Hubball and Burt (2004):

- Each assessment, and its purpose, was made as open ended as possible across all subjects and years.
- Collaborative working required a shift in teaching, learning and assessment practice so that formative and summative assessments focused on acknowledging the learning process in addition to the output. The team’s experience aligns with the findings of English et al. (2004) in that it is possible to influence student approaches to learning, particularly through assessment, which, in turn influences students’ perceptions of task requirements and hence their approach to learning.
- Embedding a wider range of methods of delivery for working within teams more closely aligned with professional industry was enhanced by engaging in internal and external student competitions.

(2) There are considerable benefits to the inclusion of a 12-week full-time work placement. The redesign of activities, use of technologies, increased exposure to practical learning at university and the workplace contributed towards mitigating against epistemological barriers, providing opportunities for greater personal development (Meyer and Land, 2006):

- The learning environment needs to recognise the link between design innovation and risk in which students are not automatically penalised for a failed design, but are encourage to analyse, learn from any failures and are rewarded accordingly for their knowledge achievement. Such a learning process has been, and continues to be, a characteristic of real-world engineering, which students need to be aware of within the context of their course.

(3) A team has to have the necessary teaching skills and resources to implement a wide range of methods of delivery and assessment:

- The teaching team need the academic freedom to innovate in teaching and share best practice whilst learning from other disciplines.
- The curriculum designer needs academic freedom to design, implement and review the curriculum with opportunities for reflection as per the process of engineering design to achieve the optimum solution.

Our study has demonstrated that the design and delivery of an innovative curriculum, within typical constraints, can provide opportunities for students to develop resilience to failure as an integral part of their learning in order to think creatively and develop novel engineering solutions. This model can be applied to other disciplines such as building surveying and construction management. This approach underpins the development of skills necessary in the educational experience to develop as a professional building pathologist.
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Failure is an option


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Effect of swine-waste bio-char on the water absorption characteristics of cement pastes

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Abstract

**Purpose** – The purpose of this paper is to investigate the effect of an admixture, Swine-waste Bio-char (SB), on the water absorption characteristics of cement pastes.

**Design/methodology/approach** – The effect of SB percentages, heat treatment temperatures, water/binder ratios, and age on the water absorption percentages (WAPs) of SB modified cement pastes were investigated using scanning electron microscopy-energy dispersive spectra, FTIR, Brunauer-Emmett-Teller, and laboratory experiments.

**Findings** – The WAPs of cement pastes with SBs produced at the low treatment temperature (LTT) of 340°C and 400°C were significantly lower \((p < 0.01)\) than pastes with SBs produced at the high treatment temperature (HTT) of 600°C and 800°C. This was attributed primarily to the more dominant presence of hydrophobic alkyl surface groups from non-volatilized matter in LTT-SBs. This had also resulted in lower surface areas and pore volumes in LTT-SBs. As a result of the volatilization of these labile hydrophobic groups at HTT, HTT-SBs were more hydrophilic and had higher surface areas and pore volumes. Consequently, HTT-SB pastes had higher WAPs and no significant differences \((p < 0.05)\) existed between HTT-SB pastes and control pastes. Also, low water/binder ratios and aging reduced water absorption of SB modified cement pastes.

**Practical implications** – LTT-SBs reduce water absorption and could reduce concrete deterioration; and as such, associated building repair, maintenance, and adaptation costs. Notably, reductions in concrete water absorption will extend the service life of concrete buildings and infrastructures, particularly in unfavorable environmental conditions. The observed benefits are tempered by the current lack of information on the effects of SB on compression strength, workability, and other durability properties.

**Social implications** – SB utilization in concrete buildings will enhance swine-waste disposal and reduce negative environmental impacts on swine farming communities; consequently, improving their quality of life.

**Originality/value** – Current bio-char research is focused on plant-derived bio-char toward soil remediation and contaminant removal, with very limited applications in concrete. This research advances knowledge for developing livestock-derived bio-char, as a PCRM, toward more sustainable and durable concrete structures.

**Keywords** Sustainability, Concrete, Cement, Bio-char, Swine-waste, Water absorption

**Paper type** Research paper
Introduction
Portland cement is a globally accepted binder that is incorporated in concrete and mortars used in the construction of new concrete buildings and infrastructure, as well as in the repair, remediation, adaptation, and maintenance of defective or damaged concrete structures (MacDonald, 2008). The performance of concrete buildings and infrastructure in service are subjected to the conditions in their surrounding environment. Most of the deteriorating influences from the environment begin from the surface of the concrete buildings and eventually negatively affect the inner concrete structure. In order to extend the service life of concrete structures, it is important to improve the resistance of concrete surfaces to unfavorable environmental conditions (Hou et al., 2015). As a critical component of the concrete material, improvements in the properties of cement, admixtures, and partial cement replacement materials contribute to the development of more resistant concrete surfaces, and consequently more durable concrete structures (Matos and Sousa-Coutinho, 2012).

Considering that cement production involves high energy consumption and greenhouse gas emissions, there continues to be a global search for new binders and admixtures that could partially replace traditional ordinary Portland cement and enhance the environmental sustainability and durability of concrete structures (Hossain et al., 2015). Durable concrete structures last long without significant deterioration by being resistant to water and other deterioration processes. While concrete is durable under normal conditions, it has the potential to fail prematurely or need costly repairs when exposed to harsh environmental conditions. Due to its porosity, concrete has the tendency to absorb water and other deleterious substances, resulting in concrete deterioration worldwide. Absorption is the process by which a liquid fills the open pores of an unsaturated porous and solid material under capillary action (Bradu and Florea, 2015; Safiuddin et al., 2011). Water penetration into concrete by capillary absorption advances the ingress of contaminative substances, microbial growth and weeds into concrete structures built in aggressive environments (Wang and Ueda, 2010). Since concrete is frequently in contact with water, water absorption in concrete has been widely researched and found to greatly affect the durability, performance, and lifetime costs of concrete structures. Considering the adverse effects of water, developing concrete and designing structures to adequately resist capillary water absorption is paramount to achieving durable structures (Hycrete, Inc., 2011).

Review of literature
While aging minimizes water absorption in concrete, low water/cement ratios and polymer modified cements have been used to develop dense and impermeable concrete to reduce water absorption in concrete (Verma and Ahmed, 2016; Ramli et al., 2013; Hossain et al., 2015; Matos and Sousa-Coutinho, 2012). In these cements, synthetic polymer phases are dispersed through the cement paste and used to seal the pores and microcracks developed during the hardening of the cement matrix (Ramli et al., 2013). Furthermore, other commercially available concrete coatings and sealers comprising of silicon, silane, silicate, silicatone, acrylic, epoxy, and urethane have been used to protect concrete (Verma and Ahmed, 2016). Although polymer modified mortars using synthetic rubber latexes and thermoplastic emulsions have been known to improve concrete durability, there are some concerns about their negative environmental impacts (Roy et al., 2001). Consequently, the use of more environmental-friendly (renewable) concrete admixtures and PCRMIs in developing more sustainable concrete composites with improved performance and durability has been a recent research focus. The use of pozzolans is encouraged as it improves concrete durability in aggressive environments (Hossain et al., 2015; Matos and Sousa-Coutinho, 2012). The utilization of industrial wastes as PCRMIs could significantly enhance the water resistance of concrete, thereby mitigating unwanted freezing, thawing, and the growth of microbes and weeds, which will ultimately improve the durability of the concrete (Nath and Sarker, 2011; Matos and Sousa-Coutinho, 2012). It is in this context that
swine-waste bio-char (SB), a waste product from the processing of bio-binder from swine-manure is of interest in this study.

Considering its toxicity, the management and disposal of swine-waste from swine-producing communities is burdensome (Ofori-Boadu et al., 2017). Data from the US Department of Agriculture revealed that in 2002 alone, five North Carolina counties had in excess of 7.5 million hogs; and they produced as much as 15.5 million tons of manure (US Government Accountability Office, 2008). Commercial swine farming has resulted in excessive swine-waste storage lagoons which have caused severe environmental impacts on surrounding communities, reducing their quality of life. This problem has spurred ongoing research on the engineering of swine and other livestock wastes in an effort to transform these wastes into more useful applications, not limited to soil remediation, contaminant removal, partial cement replacement, and asphalt rheological behavior and aging susceptibility (Fini et al., 2011; Walters et al., 2014; Cao et al., 2011; Ofori-Boadu et al., 2017). However, investigations on the application of bio-char in concrete are very limited.

Bio-char is a black carbonaceous residue obtained through a thermochemical (pyrolysis) process. Physical and chemical properties of bio-char are dictated by feedstock and production processes (Yargicoglu et al., 2015). Substantial research has been conducted on the effect of pyrolysis or heat treatment temperatures on the composition, size, density, aromaticity, porosity, hydrophobicity, and other bio-char properties (Keiluweit et al., 2010; Cantrell et al., 2012; Cao et al., 2011; Mukherjee et al., 2011; Gray et al., 2014; Jindo et al., 2014; Herbert et al., 2012; Liu et al., 2015). While treatments below 350°C produced bio-chars of which the precursor biopolymer could be recognized, high temperature chars produced mainly phenols and polycyclic aromatic hydrocarbons, which are not specific for any biopolymer (Kaal et al., 2012). Chun et al. (2004) noted that charcoals from wheat residue at 500-700°C were well carbonized and had higher specific surface area, while chars treated at 300-400°C were partially carbonized with lower specific surface areas. Compared to the precursor molecules, carbon atoms in bio-char molecules are closely packed and hence increase bio-char resistance to attack and decomposition by micro-organisms (Shackley et al., 2008).

An accumulation of tars and other organic compounds were found in low temperature bio-chars (Gell et al., 2011). Hydrophobicity is a chemical property related to residual alkyl functionalities in low temperature bio-chars, and it decreased as pyrolysis temperatures were increased (Kinney et al., 2012; Gray et al., 2014). Specifically, Kinney et al. (2012) noted that magnolia leaf bio-char varied from extremely hydrophobic when pyrolyzed at 300°C to low hydrophobicity at temperatures of 500°C and 600°C. With increasing temperatures, there is a decrease of atomic ratios H/C and O/C as a result of the removal of H- and O-containing functional groups and this result in high aromaticity in bio-chars (Ahmad et al., 2013). High temperature bio-chars have a high carbon content, large surface area, high recalcitrant nature, high aromaticity, and high adsorption characteristics (Ahmad et al., 2012; Jindo et al., 2014). Considering that temperature treatments influenced the molecular structure and pore size distribution of bio-char, they affected bio-char sorption characteristics (Ahmad et al., 2012; Keiluweit et al., 2010). As such, ongoing research has been focused on soil remediation and contaminant removal, with limited research work on bio-char applications in concrete structures.

Choi et al. (2012) noted that the high carbon content of plant-based bio-char in mortar increased the demand for water and thus affected workability. Activated carbon in optimal dosages had no effect on the performance of fresh or hardened concrete; however, improved durability was associated with the limited spalling and reinforcement exposure during concrete fire tests (DiTommaso and Bordonzotti, 2016). Bio-char addition resulted in the reduction of compression strength, and as such correct dosages of additives are needed to increase the strength of bio-char modified concrete (Elliot, 2016). DiTommaso and Bordonzotti (2016) placed emphasis on the importance of making concrete a carbon sink by incorporating
carbon-based compounds that would otherwise have decomposed in aerobic environment to produce CO₂. Considering that carbon in most organic matter is rapidly returned to the atmosphere as carbon dioxide, bio-char in concrete allows the stabilization of carbon and also removes carbon dioxide from the atmosphere (DiTommaso and Bordonzotti, 2016; Shackley et al., 2008). In their feasibility study, Ofori-Boadu et al. (2017) reported that when SB was incorporated as a PCRM in cement pastes, calcium cations from cement reacted with carboxylate anions from SB to develop calcium-polycarboxylate-salts. This occurred concurrently with the development of the typical cement paste hydration products (calcium-silicate-hydrate and calcium hydroxide); and, accelerated the setting and reduced the flow of SB modified cement pastes (Ofori-Boadu et al., 2017). Considering its carbon sequestration potential and the paucity of related research, additional insights on the effect of SB on the performance and durability of cementitious systems are critical to its full adoption as a PCRM.

Water absorption is increasingly used to quantify the durability of cementitious systems and this is an important parameter in service life models for concrete buildings and infrastructure (Fagerlund, 1996; Bentz et al., 2001; Hou et al., 2015). Concrete is only partly saturated and so the initial absorption of water and salts is, at least in part, by capillary action and heavily influenced by concrete pore volumes and pore connectivity. Concrete with high water absorption is susceptible to freezing and thawing, as water enters in the cement paste, and even in the aggregates. Furthermore, high water absorption facilitates the ingress of contaminative substances in aggressive environments resulting in concrete deterioration. Hossain et al. (2015) noted that concretes with less than 3 percent water absorption values showed excellent durability. Mohammadhosseini et al. (2017) attributed the decrease in the water absorption of carpet fiber and palm oil fuel ash modified concrete composites to the reduction in pores, which resulted from the formation of additional calcium-silicate-hydrate (C-S-H) gel through the pozzolanic reaction of palm oil fuel ash. The addition of silica fume reduced the permeability of concrete as silica fumes entered into spaces between cement particles, improving packing and reducing concrete porosity (Toutanji et al., 2004). Reduction in the porosity of fly ash modified concrete was associated with improvements that occur on the interfacial transition zones between the cement matrix and aggregates (Toutanji et al., 2004). Bernal et al. (2011) concluded that the lower water absorption of alkali activated slag concrete was because its finer, tortuous, and closed pores specimens resisted water penetration. Clearly, the physical and chemical properties of cement and partial cement replacement materials have an effect on capillary pore sizes and quantities, and this in turn, affects the water absorption characteristics of cementitious systems.

In this present research study, the researchers hypothesized that SB treatment temperatures would influence the physical and chemical properties of SB, and this would have an effect on the water absorption characteristics of SB modified cement pastes. Specifically, it was expected that SB modified cement pastes would have lower water absorption characteristics, considering that SB hydrophobicity is related to the presence of residual alkyl groups which are highly dependent on pyrolysis temperatures (Kinney et al., 2012; Gray et al., 2014; Gell et al., 2011). Furthermore, SB percentages, water/binder ratios, and age are of interest as they typically affect the water absorption characteristics of cement pastes (Hou et al., 2015; Kumar et al., 2016). To the best of the researchers’ knowledge, despite the potential carbon sequestration benefits of SB modified concrete, no research was found to have investigated the water absorption characteristics of SB modified cement pastes. Consequently, the purpose of this present research was to investigate the effect of SB on the water absorption characteristics of cement pastes. This includes assessment of the effect of SB percentages, SB treatment temperatures, water/binder ratios, and age on the water absorption percentage (WAP) of cement pastes.
Experimental materials and methods

Experimental materials were Portland cement, SB, and water. Type 1/1A Portland cement met the standard composition requirements specified by the American Society for Testing Materials (ASTM). It was purchased from a Home Depot store at North Carolina. Cement has a specific gravity of 3.15, and the bulk density of bagged cement is approximately 1000-1300 kg/m³. Mixing water was obtained from the Soils Laboratory at NC A&T State University. SB340 is the black carbon filtrate that was obtained from the sustainable infrastructural materials laboratory, which had implemented a thermochemical process (340°C under limited oxygen conditions for 80 minutes) to extract bio-oils from swine-manure (Fini et al., 2011). SB340 was obtained after the filtration process used to separate SB from oil. Beyond the heat treatment of 340°C, SB340s received additional treatments at 400°C, 600°C, and 800°C for 2 hours in a laboratory furnace in the presence of nitrogen gas, yielding specimens SB400, SB600, and SB800, respectively.

The elemental composition of each sample was obtained using the scanning electron microscopy-energy dispersive spectra. The samples were prepared by adhering the powder to an aluminum stub using carbon tape. An environmental SEM (Zeiss Evo LS-10) was used at 50 Pa operating pressure (N₂ gas) and 20 kV gun voltage. The Zetasizer Nano-S (Malvern instrument) Dynamic Light Scattering instrument was used for particle size analysis.

The textural properties of samples were determined using the Micromeritics ASAP 2020 instrument. The dry samples (0.08 g-0.2 g) were degassed in a N₂ atmosphere at a temperature of 120°C for 4 h. The degassed sample was then subjected to physisorption analysis with N₂ as the adsorbate gas in a liquid nitrogen bath at 77 K. The multilayer adsorption model by Brunauer-Emmett-Teller was used to calculate the surface area, while the pore volume was evaluated using the Barrett-Joyner-Halenda model.

FTIR analysis for surface functional groups of the samples was conducted using a Varian 670 FTIR Spectrometer with a Pike “miracle” attenuated total reflectance accessory for attenuated total internal reflection FTIR. In an ambient atmosphere, the background spectrum was collected before analyzing the samples. In total, 16 scans were recorded over the measurement range between 400 and 4000 cm⁻¹, with a spectral resolution of 4 cm⁻¹. The obtained spectra were corrected with a linear baseline.

Following the single-step method described in ASTM D7348-13, the loss of ignition (LOI) was used to estimate the volatile and organic matter in SB samples (American Society for Testing and Materials, 2013). Approximately, 1 g of SB was placed in a crucible and weighed (W₁) before combustion in a furnace. The furnace was heated at 10°C/min to gradually raise its temperature to 500°C at the end of 1 h. Heating was continued at a ramp rate of 8°C/min until temperature rose from 500°C to 950°C. The combustion temperature was maintained at 950°C for an additional 2 hours and then allowed to cool to room temperature. The crucible with SB ash was weighed (W₂). The following equation was used to calculate LOI for each sample:

\[ \text{LOI} = \frac{(W₁ - W₂) \times 100}{W₁} \] (1)

The dry bulk density (DBD) of the dry SB (10 g) samples was obtained by dividing the mass (M) of each sample by its corresponding volume (V) in a volumetric cylinder. The following equation was used to calculate the LBD of each sample:

\[ \text{DBD} = \frac{M}{V} \] (2)

Furthermore, the DBD of the dry cement/SB binder mix was obtained after manually mixing 8.5 g of cement with 1.5 g of SB for about 5 minutes to obtain a uniform dry cement/SB binder mix. The volume of the mix was measured using a volumetric cylinder. Using Equation (2), the
DBD of the 10 g blended dry cement/SB binder were also determined. Table I shows the mix proportions for all the different dry cement/SB binder blends utilized in this research study.

Following the mix design in Table I, the dry cement/SB binders were manually mixed for about 5 minutes until a homogenous mix was obtained. After that, the ASTM wet mechanical mixing process (ASTM C305-14) was followed and the wet cement pastes were placed in 50 mm × 50 mm × 50 mm cube molds and sprinkle cured for seven days at room temperature (~23°C). After initial weights of 7-day and 28-day old cement paste samples were taken, they were oven dried and weighed every 24 hours until a consistent oven dry mass \( M_0 \) was obtained. Using the volume of each cube \( V_c \), the oven dry densities (ODD) of each oven dry cube sample was obtained using the following equation:

\[
\text{ODD} = \frac{(M_0) \times 100}{V_c}
\]  

(3)

The samples were then fully immersed in water. The mass of each sample \( M_t \) was taken at specific times \( t \) after initial immersion \( t = 0 \). During the initial water absorption period, the mass \( M_t \) of each specimen at the following times \( t \) after initial water immersion: 1, 5, 10, 20, 30, 40, 50, and 60 minutes. The following equation was used to calculate the water absorption percentage (WAP\(_t\)) for each sample at the specified time \( t \):

\[
\text{WAP}_t = \frac{(M_t - M_0) \times 100}{M_0}
\]  

(4)

Results and discussions

Physical characteristics of SBs

Table II shows that with increments in SB treatment temperatures, mean particle size reduced from 822 nm for SB340 to 405 nm for SB800. Particle size reductions were attributed

<table>
<thead>
<tr>
<th>Mix design</th>
<th>Cement (%)</th>
<th>SB (%)</th>
<th>SB treatment temperature</th>
<th>Water/binder ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP0.00</td>
<td>100.00</td>
<td>0.00</td>
<td>Not applicable</td>
<td>0.28</td>
</tr>
<tr>
<td>CP1.25</td>
<td>98.75</td>
<td>1.25</td>
<td>340°C</td>
<td>0.28</td>
</tr>
<tr>
<td>CP2.50</td>
<td>97.50</td>
<td>2.50</td>
<td>340°C</td>
<td>0.28</td>
</tr>
<tr>
<td>CP5.00</td>
<td>95.00</td>
<td>5.00</td>
<td>340°C</td>
<td>0.28</td>
</tr>
<tr>
<td>CP10.00</td>
<td>90.00</td>
<td>10.00</td>
<td>340°C</td>
<td>0.28</td>
</tr>
<tr>
<td>CP15.00</td>
<td>85.00</td>
<td>15.00</td>
<td>340°C</td>
<td>0.28</td>
</tr>
<tr>
<td>CP20.00</td>
<td>80.00</td>
<td>20.00</td>
<td>340°C</td>
<td>0.28</td>
</tr>
<tr>
<td>CP0.00-NO SB</td>
<td>100.00</td>
<td>0.00</td>
<td>Not applicable</td>
<td>0.40</td>
</tr>
<tr>
<td>CP15-340</td>
<td>85.00</td>
<td>15.00</td>
<td>340°C</td>
<td>0.40</td>
</tr>
<tr>
<td>CP15-400</td>
<td>85.00</td>
<td>15.00</td>
<td>400°C</td>
<td>0.40</td>
</tr>
<tr>
<td>CP15-600</td>
<td>85.00</td>
<td>15.00</td>
<td>600°C</td>
<td>0.40</td>
</tr>
<tr>
<td>CP15-800</td>
<td>85.00</td>
<td>15.00</td>
<td>800°C</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Table I. Mix design for SB modified cement pastes

<table>
<thead>
<tr>
<th>Properties</th>
<th>SB340</th>
<th>SB400</th>
<th>SB600</th>
<th>SB800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size (nm)</td>
<td>822.017</td>
<td>545.950</td>
<td>500.300</td>
<td>405.033</td>
</tr>
<tr>
<td>Surface area (m²/g)</td>
<td>9.300</td>
<td>16.800</td>
<td>50.900</td>
<td>27.600</td>
</tr>
<tr>
<td>Pore volume (cm³/g)</td>
<td>0.041</td>
<td>0.069</td>
<td>0.162</td>
<td>0.105</td>
</tr>
<tr>
<td>Pore diameter (nm)</td>
<td>15.800</td>
<td>17.800</td>
<td>13.000</td>
<td>15.100</td>
</tr>
<tr>
<td>Loss-on-ignition (%)</td>
<td>3.630</td>
<td>1.960</td>
<td>0.960</td>
<td>0.870</td>
</tr>
<tr>
<td>Dry bulk density (g/cm³)</td>
<td>0.340</td>
<td>0.340</td>
<td>0.320</td>
<td>0.330</td>
</tr>
</tbody>
</table>

Table II. Properties of cement and SBs
to the fact that with increasing treatment temperatures, the more labile organic matter and volatile substances present on SB surfaces evaporated. In agreement with Chun et al. (2004), SB surface areas increased from 9.3 m²/g for SB340 to 50.9 m²/g for SB600. This correlated well with pore volumes which also increased from 0.041 cm³/g in SB340 to 0.105 cm³/g in SB600. According to Zhang et al. (2013), some of the bio-char pores are blocked by aliphatic and volatile constitutes and thus the lower surface areas and larger particle sizes observed in low treatment temperatures (LTT)-SBs (SB340, SB400). At high treatment temperatures (HTTs) (600°C, 800°C), the aromatization, dehydrogenation and dehydration of amorphous carbon chains to more crystalline carbons increased the total porosity. This implied that the release of the volatile components in SB resulted in the generation of more micropores in SB thereby reducing the particle sizes, while increasing the surface areas and pore volumes in HTT-SBs (Zhang et al., 2013). Zhao et al. (2017) reported a similar observation and inferred that the increase in the surface area and pore volumes were caused by the progressive degradation of organic materials.

The surface area of SB800 was ~50 percent less than that of SB600. This is indicative of the fact that the formation of the high ash content (at 800°C) resulted in the collapse of the pore structure, thereby decreasing the average pore volume and surface area, but increasing the pore diameter. The lower LOIs obtained for HTT-SBs confirmed their higher ash content and lower volatile matter when compared to the LTT-SBs. The loss of volatile matter is mostly attributed to reactions associated with organic carbon burning (Mohebbi et al., 2015). All the SBs had LOI values that were lower than the allowable maximum LOI limits specified for fly ash in ASTM C618-17 (American Society for Testing and Materials, 2017). Considering that unburned carbon in cement replacement materials such as fly ash significantly affects the color and water requirement for normal consistency in concrete mixtures, SBs with LOIs lower than specified ASTM limits are most beneficial for concrete performance (Mohebbi et al., 2015). The dry bulk densities of LTT-SBs were slightly higher than those of HTT-SBs as a result of the more dominant presence of volatile matter in LTT-SBs. However, all SB samples had bulk densities that were < 50 percent of the bulk density of cement (1.00 g/cm³). Compared to SBs, Portland cement had lower surface area (2.3 m²), pore diameter (9.4 nm), and pore volume (0.004 cm³/g).

SEM images (Figure 1) revealed the porous and amorphous surfaces of clusters of SB340, SB600, and SB800. In agreement with the pore diameter results, SB600 appeared to have the most uniform surfaces with smaller SB clusters and pore sizes. Significant textural differences were not observed in the bio-chars because they were of the same feedstock.

**Surface elemental composition**

Table III shows that carbon and oxygen were the more dominant elements in SB. Carbon content reduced from SB340 (46.9 percent) to SB600 (28.75 percent), after which it increased in SB800 (53.76 percent). This was because as treatment temperature increased from 340°C to 600°C, decarbonation of the amorphous/labile carbon portions of the organic matter (celluloses, hydrocelluloses, lignin, sugars, aminoglycans) also increased. This denotes that although the amorphous carbon content decreased with increasing temperature, the more crystalline Sp² hybridized (aromatic and olefins) recalcitrant carbon fractions of the SB (which are more resistant to thermal degradation) increased as temperature was increased to 800°C (Zhang et al., 2013; Gai et al., 2014; Gell et al., 2011). The decarbonation of amorphous carbon was accompanied by increases in the percentage of minerals (Zhang et al., 2013). The composition of minerals increased from 14.48 percent in SB340 to 26.98 percent in SB600. The reduction of minerals components from 26.98 percent in SB600 to 11.77 percent in SB800 was attributed to the melting and vaporization of minerals such as phosphorus at 800°C. Carbon content was highest in 800°C indicating high aromatization as a result of the transformation of amorphous carbon into predominantly recalcitrant (thermally resistant) Sp² hybridized aromatic carbons (Zhang et al., 2013).
The O/C ratio was highest in SB600 (1.54) and lowest in SB800 (0.64). This confirmed that at 600°C, there was significant decomposition of the mineral oxides and oxygenated salts resulting in the increase in oxygen. In contrast the very low O/C ratio at 800°C indicated that most minerals had been converted to ashes with minimal oxygen content at that temperature. Concurrently, minerals such as phosphorus were reduced as well in SB800, when compared to the lower temperature SBs. Phosphorus was the most dominant element in SB800, and this was in agreement with Zhang et al. (2013), who found phosphorus and sulfur to be the main components of the ash of pig manure derived biochars.
Surface functional groups by FTIR
Figure 2 shows that with increments in temperatures from 340°C to 600°C, there was reduction in the intensity of peaks for aliphatic C-H/CH₃ functional groups observed at 2,930 cm⁻¹, 2,860 cm⁻¹, and 1,480-1,350 cm⁻¹. In agreement with the SEM-EDX and LOI results, this loss is attributed to the decompositions of residual tars and oils that resulted in the release of H₂ and CH₄, at HTTs (Zhao et al., 2017; Gell et al., 2011). This C-H/CH₃ aliphatic peak is positively correlated with the hydrophobic behavior of bio-chars (Gray et al., 2014; Kaal et al., 2012; Kinney et al., 2012).

Compared to SB340, aromatic C=O and C=C in esters and carboxyl groups in SB600 decreased with temperature increases as indicated by the reduction in intensity peaks at 1,745-1,508 cm⁻¹. Notably, the stretches from 1,000 to 1,300 cm⁻¹ for C-O in esters and carboxyl groups were dominant in both SB340 and SB600 (Cantrell et al., 2012; Zhang et al., 2013; Liu et al., 2015).

Effect of SB percentage on water absorption
Figure 3 shows that WAPs were lower in all seven-day old hardened SB340 modified cement pastes, when compared to the control (CP0.00). Mostly, WAPs reduced with increments in SB percentages. At an LTT of 340°C and a water/binder ratio of 0.28, CP15.00 had the lowest WAP, an 88 percent reduction when compared to CP0.00. With the exception of CP1.25, significant differences (p < 0.01) existed between the WAPs of CP0.00 and all the other SB modified cement pastes. This was because the presence of hydrophobic alkyl surface groups from the residual volatile matter were more dominant in SB modified cement pastes that had higher percentages of SB and correspondingly lower percentages of cement.

<table>
<thead>
<tr>
<th>Element</th>
<th>Cement</th>
<th>SB340</th>
<th>SB400</th>
<th>SB600</th>
<th>SB800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>46.90</td>
<td>44.94</td>
<td>28.75</td>
<td>53.76</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>61.62</td>
<td>38.62</td>
<td>40.16</td>
<td>44.26</td>
<td></td>
</tr>
<tr>
<td>Calcium</td>
<td>29.94</td>
<td>3.11</td>
<td>4.28</td>
<td>9.18</td>
<td></td>
</tr>
<tr>
<td>Silicon</td>
<td>5.20</td>
<td>1.09</td>
<td>0.76</td>
<td>2.21</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.90</td>
<td>ND</td>
<td>0.49</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Sulfur</td>
<td>ND</td>
<td>ND</td>
<td>0.85</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>4.32</td>
<td>2.78</td>
<td>4.12</td>
<td>2.67</td>
<td></td>
</tr>
<tr>
<td>Phosphorus</td>
<td>ND</td>
<td>5.96</td>
<td>5.75</td>
<td>10.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.12</td>
<td></td>
</tr>
</tbody>
</table>

*Note: ND, not detected*

**Table III.** Percent composition (elemental analysis) of cement and SBs

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Effect of swine-waste bio-char...
The FTIR spectra in Figure 4 confirmed the results from Figure 3. It can be seen that the reduction in WAPs of SB modified cement pastes is mostly attributed to the presence of hydrophobic aliphatic C-H surface functional groups in residual bio-oils and tars that were unable to escape at 340°C (Gell et al., 2011; Kinney et al., 2012; Gray et al., 2014). The stretches at 2,850 cm\(^{-1}\) and 2,917 cm\(^{-1}\) in CP10 and CP15 were due to the hydrophobic alkyl surface groups in SB modified cement pastes (Kinney et al., 2012). The capillary pores of these SB modified cement pastes were functionalized with hydrophobic alkyl groups that rendered their surfaces hydrophobic, and thus created negative capillary forces in the pores of the cement pastes, which effectively resisted, and reduced water entry into the pastes (Gray et al., 2014). With increments of SB in cement pastes, the presence of these hydrophobic alkyl surface functional groups increased and this reduced WAPs in SB modified cement pastes.

Despite the fact that cement had lower surface areas (2.3 m\(^2\)) and smaller pore volumes (0.004 cm\(^3\)/g) when compared to SB340, the control cement pastes (CP0.00) still absorbed more water. This confirmed that SB surface functional groups, and not textural properties, greatly influenced the water absorption differences observed between the control cement paste (CP0.00) and the SB modified cement pastes. As shown in Figure 4, the stretches at 2,850 cm\(^{-1}\) and 2,917 cm\(^{-1}\) in CP10 and CP15 for hydrophobic surface groups in SB modified cement pastes are noticeably missing in CP0.00. The presence of hydrophobic surface groups and the lowest WAP in CP15 signified with that, cement pastes with up to 15 percent of SB340 demonstrated the best potential to reduce water absorption, and
consequently, improve the durability of concrete in aggressive environments. Studies by Hossain et al. (2015) corroborated that concretes with < 3 percent water absorption values showed excellent durability.

**Effect of water/binder ratio on water absorption**
Figure 5 shows that SB modified cement pastes with the higher water/binder ratio (0.4) had higher WAPs. Compared to the 0.40 water/binder paste, there was a 72.89 percent reduction in the WAPs of the 0.28 water/binder pastes. The differences were statistically significant \( (p < 0.01) \), and attributed to the higher water content in the 0.40 paste.

This resulted in a greater volume of the pastes being occupied by water, and thus resulting in a less dense paste with a weaker microstructure. Upon the evaporation of excess water during oven heating, the escaped water left greater voids in the 0.4 pastes (Pitroda and Umrigar, 2013). This led to an overall increase in the capillary porosity of the 0.4 water/binder pastes, and consequently, a more positive water sucking pressure that imbibed more water to fill the empty capillary pores within the pastes. This is in agreement with Hou et al. (2015) who noted that cement pastes with higher water content typically have larger pore volumes and thus have higher water absorption (Hou et al., 2015).

**Effect of SB treatment temperatures on the water absorption**
Among all the seven-day old samples, Figure 6 shows that CP15-340 had the lowest WAP. Compared to the control paste, a 67.27 percent reduction was observed in CP15-340 and this difference was statistically significant \( (p < 0.01) \). Furthermore, a wide gap existed between the WAPs of LTT-SB pastes (CP15-340 and CP15-400) and those of HTT-SB pastes (CP15-600 and CP15-800). No significant differences were observed between the HTT-SB cement pastes and the control pastes.

Results shown in Figure 6 were in agreement with the FTIR analysis in Figure 7 which revealed that the main difference between the WAPs of the LTT-SB pastes and the HTT-SB pastes was attributable to the presence of hydrophobic alkyl groups (C-H at 2,858 cm\(^{-1}\) and 2,927 cm\(^{-1}\)) in LTT-SB pastes (CP15-400). The C-H peaks were dominant in LTT-SB cement pastes because there were still unburned organic matter in LTT-SBs. LOI results from Table III confirmed that the hydrophobic surface functional groups originated from volatile...
matter that were more dominant in LTT-SBs, compared to HTT-SBs. The long chains of these non-polar hydrophobic alkyl groups were responsible for the water repulsion and the negative capillary pressure in the LTT-SB cement paste pores and contributed to the reduction in their WAPs. Figure 7 shows that no CH peaks (2,848 cm\(^{-1}\), 2,917 cm\(^{-1}\)) for alkyl groups were detected in CP15-600 and CP0.00-NO SB. These alkyl groups are noticeably absent in CP0.00-NO SB because it had no SB and as such no organic matter. Furthermore, the presence of these alkyl groups in LTT-SBs contributed to the higher LOIs, and the lower surface areas and pore volumes of LTT-SBs (Table II). These properties minimized SB surfaces available for sorption. Therefore, textural properties also contributed to the differences between the WAPs obtained for LTT-SB cement pastes and HTT-SB cement pastes.

Contrary to LTT-SB cement pastes, HTT-SB pastes (CP15-600, CP15-800) had WAPs similar to the control paste. Notably, no statistically significant differences (\(p < 0.05\)) existed among control pastes (CP0.00-NO SB), CP15-600, and CP15-800. From Figure 6, CP15-600 and CP15-800 pastes conspicuously absorbed more water. This could be attributed to the fact that at HTTs, there is significant decarbonation/devolatilization of the amorphous hydrophobic alkyl chains leaving behind mostly crystalline and aromatic \(\text{Sp}^2\) hybridized carbon moieties which are relatively more hydrophilic in nature. Additionally, at HTTs, the WAPs increased due to the relative increase in the amount of mineral oxides/salts which are polar/ionic and further facilitate the absorption of water. Similarly, Ahmad et al. (2012) and Jindo et al. (2014) observed high temperature bio-chars have a high carbon content, large surface area, high recalcitrant nature, high aromaticity, and high adsorption characteristics.
CP15-600 had the highest WAPs because coupled with the lack of hydrophobic alkyl groups, CP15-600 was modified with SB600, which had the highest surface areas and pore volumes (Table II). However, compared to CP15-600, CP15-800 had a slightly lower WAP because it had slightly lower surface areas and pore volumes (Table II). Considering its low LOI and high mineral content, this was attributed to the high ash content in SB800 which had degraded the pores and as such resulted in a slight reduction of its surface areas and pore volumes.

Table IV shows that the control cement and pastes had higher DBDs and ODDs when compared to SB modified binders and their respective pastes. The lower bulk densities of SB modified powders and their associated pastes were as a result of the lower dry densities of the SBs (Table II) that were used to partially replace cement in the SB modified pastes (Ban and Ramli, 2011).

Despite the higher densities associated with control pastes, they had higher WAPs. This provided a strong indication that the lower WAPs observed in LTT-SB modified cement pastes were not associated with their lower oven dry densities, but rather mostly resulted from the hydrophobic behavior of the surface functional groups of LTT-SBs.

**Effect of aging on water absorption**

Figure 8 shows that WAPs for seven-day specimens were higher than those of 28-day pastes indicating that resistance to water penetration improved with age. Although not statistically significant, the WAP for the seven-day old specimen was 8.34 percent higher than that of the 28-day old pastes.

This can be attributed to the fact that with the longer hydration period, there was a more complete development of the hydrated products and this reduced the capillary pores and therefore lowered the suction of water into the cement pastes. This reduced the water absorbed and lowered the WAP for the older samples, which were the 28-day old CP15-400.

In summary, SB treatment temperatures modified SB chemical composition and textural properties. Notably, LTT increased hydrophobicity of SB, while higher temperature treatments increased hydrophilicity. Consequently, the changes in the physical and chemical properties of SB exhibited a profound effect on the WAPs of SB modified cement pastes. This is in agreement with Ahmad et al. (2012) and Keiluweit et al. (2010). By homogeneously mixing water with the dry cement/SB binder, SB was dispersed within the cement paste matrix. As hydration progressed and capillary water was consumed, key hydration products grew into

<table>
<thead>
<tr>
<th>Mix design</th>
<th>CP0.00-NO SB</th>
<th>CP15-340</th>
<th>CP15-400</th>
<th>CP15-600</th>
<th>CP15-800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry bulk density of dry binders (g/cm³)</td>
<td>1.00</td>
<td>0.75</td>
<td>0.69</td>
<td>0.68</td>
<td>0.71</td>
</tr>
<tr>
<td>Oven dry density of hardened cement pastes (g/cm³)</td>
<td>1.64</td>
<td>1.57</td>
<td>1.40</td>
<td>1.57</td>
<td>1.59</td>
</tr>
</tbody>
</table>

Table IV. Densities of SB modified cements and hardened cement pastes

![Figure 8.](image-url) Water absorption of CP15-400 cement pastes at different ages
the pore space that was originally occupied by water (Hou et al., 2015). The cement paste then set and developed strength; however, with capillary porosity within the cement paste matrix. The presence of hydrophobic alkyl functional groups from LTT-SB altered surface chemistry of the capillary pores within the hardened LTT-SB modified cement paste. Considering that these pores provided the primary transport routes in and out of the cement paste, changes in the surface chemistry of the pores reduced capillary water absorption; and this will eventually improve the durability of the cement pastes and concrete buildings (Fagerlund, 1996; Bentz et al., 2001; Hou et al., 2015).

Conclusion
This research investigated the effect of SB on the water absorption characteristics of cement pastes. Research findings showed that treatment temperatures during SB production greatly affected SB surface functional groups and textural properties, which ultimately had a significant effect on the water absorption characteristics of SB modified cement pastes. WAPs of cement pastes with SBs produced at the Low Treatment Temperatures, were significantly lower (p < 0.01) than pastes with SBs produced at the HTTs. Under the experimental conditions, the LTT-SBs, particularly SB340 with a 15 percent cement replacement percentage, demonstrated the best potential to reduce water absorption in cement pastes. This was attributed to the dominant presence of hydrophobic alkyl surface functional groups, as well as to their lower surface areas and pore volumes. On the other hand, the cement pastes with HTT-SBs, particularly SB600, demonstrated the least potential to reduce water absorption. These pastes were similar to the control pastes. This was attributed to the fact that at HTTs, there was significant decarbonation/devolatilization of the amorphous hydrophobic alkyl chains leaving behind mostly the crystalline and aromatic $sp^2$ hybridized carbon moieties which are relatively more hydrophilic in nature. Additionally, the relative increase in the water absorption of HTT-SB cement pastes was due to the relative increase in the presence of SB mineral oxides/salts which are polar and further enhance the absorption of water. Also, low water/binder ratios and aging reduced water absorption in SB pastes.

Considering that water absorption has a direct relationship with concrete durability, LTT-SBs should be further studied and considered as a good partial cement replacement material which could improve the durability and service life of concrete structures. Improved durability will undoubtedly reduce concrete deterioration and maintenance costs. In the long term, SB could present economic and environmental benefits to swine farming communities.

References


Effect of swine-waste bio-char


Further reading


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Review and assessment of the causes of deficiencies in design documents for large construction projects

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Abstract

Purpose – Design documents’ deficiencies (DDDs) are a major issue that plagues the construction industry in many countries. The purpose of this paper is to investigate the major causes of DDDs in a fast expanding economy, where errors can translate to an adverse impact on the economy. This paper aims to identify and assess the causes of DDDs for large construction projects from the consultants’ perspective.

Design/methodology/approach – In total, 20 causes of DDDs were shortlisted through an extensive literature survey. In total, 37 consultants based in the Eastern Province of Saudi Arabia participated in the study. The respondents were requested to provide their opinion with respect to the relative importance of the identified causes. The result of their responses was then used to rank the causes.

Findings – Based on their significance indices, the most significant causes of DDDs were “assigning design tasks to designers who lack work experience,” “team members’ communication skills,” “the level and quality of the design professional’s education,” “cross-disciplinary coordination,” “effective design team,” and “lack of knowledge transfer mechanism.”

Practical implications – Recommendations were provided to mitigate the issues of DDDs. It is envisioned that through a better understanding of the major causes of DDDs, design firms will be better positioned to recognize DDDs’ causes and establish appropriate measures for reducing their occurrence. The findings of this paper are beneficial to all project stakeholders, including design firms, clients, contractors, and end users.

Originality/value – This paper contributes to the literature by providing an assessment of the various causes of DDDs in the context of a rapidly expanding economy, where any inefficiency can lead to massive losses to the economy.

Keywords Client, Design management, Design documents’ deficiencies, Design errors, Team composition

Paper type Research paper

Introduction

Estimated to be worth more than a $3.9 trillion annually, the world of construction is an enterprise of colossal proportion (Alzara et al., 2016). It is evident that with such large sums of money at stake, efficiency is crucial. It is therefore understandable that the completion of a project within the originally specified time, budget, and quality are viewed as key indicators of a successful project (Assaf and Al-Hejji, 2006; Ameh et al., 2010). In practice, however, given the highly complex, ever-changing character of the construction process (Banaitiene and Banaitis, 2012), such standards tend to be elusive (Ameh et al., 2010; Hwang et al., 2009).
More specifically, the construction process is subject to a multitude of variables that may impede its progress. Such variables encompass the performance of the various construction parties, the supply of resources, and environmental factors to name a few (Arain et al., 2006). With respect to the performance of parties, design professionals play a significant role in influencing the successful development of the project. For example, poorly prepared design documents cause construction inefficiencies, increase the likelihood of litigations, and raise costs (Tilley and Barton, 1997). Poorly prepared documents also lead to inaccuracies in estimates (Laryea, 2011), opening the door to opportunism (Laryea, 2011). Specifically, contractors who notice poor design will apply contingencies to their estimates to compensate for any potential future expenses. For example, in De Neufville and King’s (1991) study, the quality of design was one of the most frequently chosen project-risk factor by the contractors. In addition, contractors aware of issues in documents will choose not to divulge such defects at the bidding stage, with the intent of raising claims during the construction stages (Laryea, 2011). At the extreme end, design errors can even precipitate failures (Palaneeswaran et al., 2007).

The construction process can be partitioned into three broad stages. These include the project’s conception, design, and construction. It is widely acknowledged that the second stage, the design process, heavily sways the entire life cycle cost of the project (McGeorge, 1988; Kangari, 1995; Chan and Kumaraswamy, 1997; Tilley and Barton, 1997; Kartam and Kartam, 2001), despite its relatively low cost (Senescu et al., 2013). It is not surprising, then, that the management of the design process is a subject of great importance to the architecture/engineering/construction industry (Chua et al., 2003). Given its magnitude in relation to the cost of a project, recent trends in the field are a cause for concern. According to Slater and Radford (2012), there has been growing perception in the industry that the standard of design documentation and specifications has been on the decline.

Considering the above discussion, it follows that an awareness of the various causes that undermine the quality of design documentation, such as inexperience of designers and lack of training, is of great importance toward realizing a successful project (Andi, 2005). To that end, the objective of this study is to identify and assess the major causes of design documents’ deficiencies (DDDs) for large construction projects, which will enable proper actions to be taken to prevent them from arising. The outcomes of the study will directly lead to an enhancement in the design firm’s operations, profitability, reputation, as well as their competitiveness (Love et al., 2008; Sunday and Afolarin, 2013). Apart from the outlined benefits gained by design consultants, and equally as important, other stakeholders will also see many benefits from the efficiency gains. These stakeholders include owners who will be protected from the consequences of soaring costs and delays; contractors who will see their fixed costs plummet as the time spent on projects decreases; and end users who will be protected from the inconvenience and safety hazards posed by constructed structures, which are based on faulty design documents. The main contribution of the study is providing insights into the most significant causes of DDDs, thus, raising awareness among design professionals and assisting them in focusing their attention and resources on potential causes of DDDs. This study is distinct from previous studies in that it offers a sharp, extensive, and up-to-date focus on the issue of DDDs causes.

The paper adopts the following structure. First, the research methodology adopted to undertake the study is introduced along with its justification. This is then followed by the literature review, which contextualizes the problems as well as discusses the causes of DDDs by drawing from previous studies. Next, the analysis and findings of the field observation are communicated. These findings are arranged into four themes to give different perspectives on the causes of DDDs.
Research methodology

The following activities were conducted toward achieving the objectives of the research:

- Reviewing the relevant literature (Barkow, 1995; Tilley, 1998; Andi and Minato, 2003; Johansen and Carson, 2003; Darwish, 2005; Mohammed, 2007; Slater and Radford, 2012; Mryyian and Tzortzopoulos, 2013; Sunday and Afolarin, 2013; Zidan, 2013; Dosumu et al., 2017) to identify the major causes of DDDs in large construction projects. In total, 20 causes were identified and categorized under four groups.

- Interviewing a sample of five professionals in the building construction industry (as a first level of quality and comprehensiveness check). These professionals included an architect, two civil engineers, a mechanical engineer, and an electrical engineer. These professionals were selected based on convenience sampling, availability of professionals, and the professional's willingness to participate in the study. These professionals had a minimum of five years of experience in the construction industry. The interviews served to confirm the relevance, comprehensiveness, and clarity of the identified causes of DDDs.

- Developing a questionnaire survey to assess the significance of the identified causes of DDDs. Based on the outcomes of the literature review as well as the inputs of the professionals, a questionnaire survey was then developed. The questionnaire solicited the respondents' assessment of the 20 causes through a five-point Likert scale. The 20 causes, which were classified into four categories, based on a common theme shared by the causes and according to various units that constitute a design organization, in addition to one external factor. The classifications of the causes under their respective categories were also confirmed by the interviewees.

- Pilot-testing the questionnaire survey with the assistance of five participants in the study (as a second level of quality and comprehensiveness check). The pilot-testing served to ascertain the validity of the identified DDDs, and enhance the clarity of the identified causes.

- Obtaining responses from 37 consultants, practicing in the Eastern Province of Saudi Arabia. The objective of the assessment was to gain insights into which of the identified causes were viewed by the consultants as being the major causes of DDDs. The significance indices (Dominowski, 1980) of the causes DDDs were computed to determine the consensus among the participants on the criticality of the identified causes. Computing the significance indices also helped in ranking the identified causes, and hence, identifying priorities for improvement, indicating where to direct resources for improving the level of professional practice.

- Analyzing the received responses to identify the level of significance of the identified causes, as well as the ranking of these causes. Descriptive statistics was also employed to test the degree of dispersion of the data.

Figure 1 is a flowchart of the methodology followed to achieve the objectives of the research.

Previous studies

Design deficiency consists of an error or omission which leads to the construction of a facility that fails to achieve its intended goal (Buhshait et al., 1998). The presence of design deficiency has been widely accepted as a sign of dysfunctional organizational and managerial practices in construction. Past studies (Al-Far, 2005; Love et al., 2006, 2008; Palaneeswaran et al., 2007; Laryea, 2011) have, at varying degrees, explored the subject of DDDs’ causation.
The level of experience possessed by a professional is critical to the production of sound design documents, which unambiguously convey the desired goal. The significance of adequate experience has been demonstrated by Acharya et al. (2006) who indicated that the designer’s lack of experience subjected a design firm to increased cost and a tarnished image. Although the causes of DDDs may seem minor at first, they can have devastating impacts on the project. A study by Haydl and Nikiel (2000) found that a construction failure which amounted to a costly design change stemmed from a calculation error committed by the designer. The study highlighted that the cause of error was due to the designer’s insufficient knowledge of fundamental engineering procedures. Surprisingly, despite the advancement in technology, such as BIM (Rajendran et al., 2013; Regan et al., 2015; Wang, 2017), and a growing body of construction literature detailing various solutions to combat DDDs, DDDs continue to afflict the industry. This proliferation of design deficiencies, as noted by Vlatas (1986), is due to the increasing complexity of the construction work, emerging new and different relationships between the design and construction professionals, and the increasing demand to complete projects in less time.

Despite the greater demand for higher performance being imposed on designers, the designer’s compensation structures have not seen a corresponding improvement. This has had an adverse effect on the quality of design documents. Numerous studies support this view. For example, Abolnour (1994) demonstrated the existence of a non-linear inverse relationship between design-related problems and the design fee level. Unfortunately, owners have not realized the truth of this fact, opting for lower design fees in the hopes of cutting expenses. This misconception is apparent from the selection procedure employed by the owners, which favor low-cost services. Researchers have shown the flaw of this line of thinking. For example, according to DeFrates (1989), when the method of selecting designers is based on the lowest fees, the owner is likely to experience added cost due to a limitation in the amount of design services. This view was also echoed by Andi and Minato (2003), who concluded that the “low fee structures of designer” together with “insufficient overall design time” were two principal causes that affected the design’s document quality.
Dosumu and Iyagba (2013) found that consultants perceived “insufficient fund to create quality document” and “designer experience” as among the top causes of DDDs. Furthermore, Babshait et al. (1998), who developed a statistical model which related design fee and design deficiency, found a negative correlation between design deficiency cost of a project and the design fee. Contractors are also aware of the impacts of low fees on the design documents (Tilley, 1998).

Time is a crucial element in the production of error-free and complete design documents. A recent study by Dosumu et al. (2017) found inadequate time to be among the most significant causes of DDDs. Through interviews and written responses from construction professionals, Johansen and Carson (2003) found that the key issues needed to be addressed in order to improve the design practice were the amount of design time allotted, thoroughness of briefing, and a team-based approach. Darwish (2005) investigated the key factors effecting design and documentation quality in Saudi Arabia’s construction industry. The study found insufficient time and the consultant’s tendency to reuse drawings from previous work to be among the major factors contributing to DDDs. Zidan (2013) conducted a study to determine the main factors effecting the construction industry’s design quality. It was revealed that lack of design time and low design fees were among the significant contributors. Slater and Radford (2012), who interviewed and distributed questionnaires to construction professionals, discovered that the main factors leading to poor architectural documentation from the perspective of the professionals were insufficient design time, improper employment of technology, work overload, low design fee, and lack of coordination.

The reuse of previous work, although being a practice that relieves pressure, can be a source of poor design documents, if not performed properly. Several studies have shown this to be the case (Mohammed, 2007; Palaneeswaran et al., 2007; Love, Lopez, Edwards and Goh, 2012). For example, studying the main causes effecting design and documentation quality, Al-Far (2005) determined that the tendency of consultants to copy and modify design from their past work was regarded as a major cause of DDDs.

The availability of key personnel, skills possessed by these personnel, in addition to their coordination can be influential to the level of DDDs experienced by a design firm. For instance, several causes pertaining to the design firm’s personnel that influenced design deficiency were identified by Abolnour (1994). These causes included shortage of construction managers, shortage of personnel within the design office, and the lack of experience of the chief structural engineer. Likewise, Sunday and Afolarin (2013) concluded that “professionals” inexperience was among the main causes of errors in construction documents. Knowledge is crucial to reducing the number of errors experienced. Haydl and Nikiel (2000) indicated that design errors largely result from the insufficient comprehension of fundamental engineering methods, poor details’ development, or in some cases as a consequence of “last minute” changes without due consideration of the implications of these changes. In addition to knowledge, another important factor is communication. Barkow (1995) who conducted a literature review of human factors underlying building failures found that insufficient knowledge and inadequate communication were among the causes of human error. The study conducted by Love et al. (2006) found that the significance of personnel coordination could be a more crucial determinant of rework, than the improper utilization of technology. In particular, the study found that design consultants ranked “poor coordination of design team members” as the most significant cause of design rework, while “ineffective use of information technologies” was ranked last.

The causes of DDDs can also originate from factors that are external to the design firm. For example, in their study of the perceived causes of error and waste in residential buildings, Mryyian and Tzortzopoulos (2013) observed that the design professionals attributed the major cause of design errors to external factors, namely, client changes. Love et al. (2014) noted that the adoption of competitive tendering by the owners as a
criterion for selecting designers leads to less emphasis being placed on design quality management. Another outcome of this selection approach is the generation of substandard documents, as a consequence of cost cutting measures taken by designers (Love, Davis, Cheung and Irani, 2011; Love, Edwards, Han and Goh, 2011). Errors can also arise because of erroneous assumptions made due to inadequate project briefing at the initial stages of a project (Sun and Meng, 2009).

As outlined above, the causes of DDDs are numerous and can originate from either the design firm or the client. If DDDs are to be eliminated or reduced, an understanding of the main contributors of DDDs as they relate to these two entities is crucial.

Causes contributing to DDDs

Based on the survey of the literature, a total of 20 causes of DDDs were considered. Interviews were also conducted with a sample of five professionals in the building construction industry to confirm the relevance of the identified causes of DDDs. The interviewees included an architect, two civil engineers, a mechanical engineer, as well as an electrical engineer. These professionals had a minimum of five years of experience in the construction industry in various types of projects, ranging from residential, commercial to institutional projects.

With respect to the classification system, Barkow (1995) divided human factors causing design errors into three categories, including technical procedures, organizational and managerial, and individual behavioral factors. Mohammed (2007) classified the causes of DDD into four categories based on the organization that contributed to their generation, namely, management, designers, clients, and project characters. Dosumu and Iyagba (2013) extended Mohammed’s (2007) categorization by incorporating a fifth category, industry-related factors. Finally, Atkinson (1998) grouped the causes of DDD into three groups, including primary, management, and global factors. In light of these previous studies, the identified causes in this study were divided into four categories with the primary goal of facilitating the assessment of the extent to which various design firm organizational levels and external factors could influence the occurrence of DDD. These categories comprised “causes pertaining to staff at the design office,” or individual-based factors, “composition of the design team,” or team-based factors, “design management of the project,” or management-based factors, and “client’s involvement in the project,” or external factors.

Causes pertaining to staff at the design office

The level and quality of the design professional’s education. The level as well as the quality of education of the members of the design team have a strong bearing on the completeness and correctness of the prepared design documents. A well-educated designer will have the required knowledge to prepare the design documents, find solutions to problems, and will be capable of communicating, as well as coordinating with the various disciplines (Mohammed, 2007).

Challenges in retaining qualified staff. This cause relates to the challenge of retaining well-qualified staff in the design office. This problem exists because when professionals acquire more experience, they naturally seek better positions in other firms (Tilley and Barton, 1997; Andi and Minato, 2003; Al-Far, 2005).

Lack of staff in the design firm. This cause relates to how insufficient manpower influences DDDs. A design firm having an adequate staff level will create a stress-free working environment in terms of less workload. This, in turn, will encourage knowledge circulation and reduce the pressure among the staff. Such an environment that permits knowledge transfer will lead to an increase in experience, which, ultimately, produces the desirable effect of having less DDDs (Arain et al., 2006).
Change in staff during the project. It has been identified that personnel play a significant role in the success or failure of a project. Aggarwal and Rezaee (1996) underscored the significance of personnel to an organization by stating that in many occasions, management were forced to discontinue projects as a result of staff turnover. The reason for this is due to the disruption together with the “knowledge vacuum” that arises in the aftermath of losing a staff member (Love, Davis, Cheung and Irani, 2011; Love, Edwards, Han and Goh, 2011). Luth (2000) proposed that “special precautions” should be conducted to ensure a “smooth transition” whenever there is a change in staff.

Overreliance on software tools. This cause relates to software used by the team for the design development of the project and their effect on DDDs. Errors can stem from heavy dependence on computer aided automation, in which there is a failure to consider the practicality of the design solution (Lopez et al., 2010; Andi and Minato, 2003). Additionally, staff may not be properly trained to utilize adopted software tools (Al-Far, 2005).

Causes pertaining to the composition of the design team
Team members’ communication skills. This cause relates to the level of communication between the design team members and its effects on DDDs. Communication is defined as the exchange of “thoughts, messages, or information,” which can be achieved through oral, written or visual means (Tilley, 2005). Since the goal of the design team is to develop an optimal design solution through knowledge and information sharing, working in a design team requires team members who possess the necessary skills to communicate and collaborate effectively (Brown, 2002; Andi and Minato, 2003).

Effective design team. This cause relates to how the effectiveness of a design team affects DDDs. An effective design team is characterized by the following attributes: undertaking interactive and all-inclusive discussions; understanding other team members’ roles and skills; hosting the right blend of “functional/technical, problem solving, and interpersonal skills” among its team members; possessing a specific set of individual and organizational targets; setting realistic goals which are well-defined and valued by all the team members; and possessing team members who all have a sense of equal accountability. The formation of such an effective team will mean that issues pertaining to DDDs will drop. This is made possible since the entire team will leverage and improve the skills of the members who constitute the team, while at the same time altering and enhancing the work as time elapses (Mohammed, 2007).

Design team cohesiveness. This cause relates to how the compatibility of team members affects the completeness, correctness, and the clarity of the design documents. Compatibility refers to the degree to which an individual connects with their co-workers. Since people are different, situations may arise where there is either attraction or repulsion between team members. This relationship between the team members will directly influence the effectiveness of the team, in either a positive, or a negative manner. In the unfavorable instance where the team members disagree with each other, communication will suffer, dissemination of knowledge will be impeded, and DDDs will begin to multiply (Mohammed, 2007).

Causes pertaining to the design management of the project
Assigning design tasks to designers who lack work experience. The level of experience possessed by the designer will greatly shape the amount of DDDs. This cause relates to how DDDs could be affected by the practice of utilizing the services of incompetent personnel such as undergraduates, recent graduates, or inexperienced part-time staff to perform advanced technical tasks (Tilley and Barton, 1997; Love and Li, 2000; Love et al., 2006). Employing such a practice has negative consequences. First, since personnel lacking experience may not always be familiar with the processes and practices adopted by an
organization, they are more susceptible to commit errors (Lopez et al., 2010). Second, personnel who lack experience tend to consume more time in performing tasks, generate more errors (Mohammed, 2007), and require more supervision, relative to their more experienced counterparts. Lastly, these personnel lack the adequate experience and the construction knowledge needed to prepare complete and accurate design documents (Andi and Minato, 2003).

**Cross-disciplinary coordination.** This cause relates to the impact of lack of coordination between the members of the design firm and its effects on DDDs. The building design process consists of a team of diverse specialties, each independently making decisions related to their disciplines, while at the same time having to ensure that the coordination of these decisions is maintained at all times (Mokhtar et al., 1998). There are two issues under this category. The first is related to the poor management practice of not assigning a single person/office the responsibility of coordinating with other disciplines (Al-Far, 2005). The second issue involves designers working in isolation and making decisions without considering their implications on other disciplines. Such practices create barriers between the project teams (Love, Lopez, Edwards and Goh, 2012).

**Lack of knowledge transfer mechanism.** This cause relates to the transfer of knowledge within an organization and its effects on DDDs. One of the main causes of DDDs is the absence of mechanisms by which members of the design team receive feedback and learn from past errors (Mohammed, 2007). Many design consultants are inclined to conceal their errors owning to “commercial pressure or personal esteem” (Love, Lopez, Edwards and Goh, 2012). This shortcoming in the operation of the organization hinders its ability to learn from previous experiences. Love et al. (2008) explained that despite the availability of numerous lessons to be gained from the successes and failures of projects as well the technological advancement that has been experienced, design errors continue to abound in construction projects. This is attributed to the refusal of organizations to properly reflect on past projects. Mistakes committed in past projects, as a consequence, are repeated.

**Absence of quality management practices during the design phase.** This cause relates to the absence of quality management practices during the design phase. Despite the importance of quality assurance, some design firms choose not to perform this crucial activity due to significant workloads or insufficient time to review the design documents. In some cases, design firms may view quality assurance measures such as “audits, checks, and verifications” as non-value adding activities. It is important for designers to realize that such views are unfounded since the quality of the design documents has significant implications on both the overall cost of the project as well as the design firm’s profit (Lopez et al., 2010).

**Designers engaging in simultaneous work.** This cause relates to simultaneous work and its effect on DDDs. Undertaking a multitude of activities at the same time makes planning more challenging. The means of communication adopted, accordingly, will be a major determinant of the effectiveness of individual designers. Briefly, as the volume of simultaneous work rises, the documents susceptibility to DDDs will correspondingly rise (Mohammed, 2007).

**Lack of training programs offered to the design team.** The issue of inadequate training is considered to be an organizational factor that contributes to DDDs (Love, Lopez, Kim and Kim, 2012). It has been suggested that insufficient training offered by senior staff could translate to an erosion in the “knowledge base” of future designers (Tilley and Burton, 1997). Andi and Minato (2003) recommended the frequent involvement of designers in the construction process to achieve a better understanding of the activities of the construction phase.

**Reuse of construction specifications and design details.** This cause relates to the reuse of design details and its effect on DDDs. This cause is associated with timeboxing and the
design firm’s workload. As the time given to perform a task shrinks, or as the amount work mounts, designers may resort to borrowing details and specifications from other projects to reusing them in others. Sometimes these specifications and design details are incompatible with the requirements of the current project (Love, Lopez, Edwards and Goh, 2012). While, it is a common practice to reuse construction specifications and design details, diligence should be exercised in conducting the necessary modifications to make details compatible with the concerned project, especially when the design is unique (Palaneeswaran et al., 2007).

Use of timeboxing to complete design tasks. This cause relates to the impact of assigning a fixed time, known as “timeboxing,” to the design process and the impact this would have on DDDs. In other words, regardless of the status of the task, designers are forced to submit the documents in the allotted time (Love and Edwards, 2004). Although adopted as a way of controlling resource expenses, such measures may mean that important tasks such as audits, reviews, and verifications are neglected. This paves the way for the occurrence of errors at the construction stage (Love et al., 2008). The use of timeboxing ultimately results in additional cost and a damaged image for the design firm (Palaneeswaran et al., 2007). Furthermore, when designers are faced with limited time, the quantity of simultaneous activities undertaken rises. This diminishes the amount of coordination and communication, which lowers the amount of problems resolved. The outcome will be construction documents having more errors (Andi and Minato, 2003; Arain et al., 2006).

Accepting low design fee. This cause relates to the consequences of the low design fees on DDDs. It has been recognized that a positive correlation exists between fees and the quality of the design documents, which ultimately impacts the performance of a project (Al-Far, 2005; Love et al., 2006). Usually, low design fees result in poor design documents submitted to clients (Tilley and Barton, 1997; Andi and Minato, 2003; Laryea, 2011). Consequently, in many instances the designer may employ inexperienced staff to cut back on the expenses of preparing design documents. This practice has a negative impact on the quality of the design documents (Lopez et al., 2010).

Causes pertaining to the client’s involvement in the project

Designer’s failure to understand client’s intent. This cause relates to the misinterpretation of the client’s intent and its effect on DDDs. Love et al. (1999) indicated that misinterpretation of the client’s intent and/or the designer’s inability to completely comprehend the client’s requirements are responsible for DDDs, and ultimately rework. The amount of time the designer spends with the client can have a strong bearing in grasping the clients’ intent (Tilley, 2005). Al-Far (2005) stressed the need for designers to spend sufficient time with the client to the extent that a complete picture of the project’s requirements is attained.

Unrealistic client demands. This cause relates to the unrealistic demands, in terms of fees and time, imposed by clients on the designers (Andi and Minato, 2003; Love et al., 2008, 2010). These impractical expectations result in substantial stress for designers, especially when the process of selecting them is based on competitive bidding (i.e. low design fees) (DeFraites, 1989). Such demands can lead to undesirable consequences, which set the stage for DDDs. Tilley and McFallen (2000) founded as clients expedited the project’s completion time, designers were more likely to produce contract documents that contained errors (Love et al., 2006).

Client experience. This cause relates to the effect of the client’s experience on the quality of communication with the design team (Love et al., 2008). Absence of proper communication between the client and the design team adversely affects the project, which ultimately results in the preparation of poor design documents. This becomes more severe when the client does not possess adequate background in construction (Andi and Minato, 2003; Love et al., 2004; Lopez et al., 2010).
Assessment of the causes of DDDs

The authors opted to use a recognized research methodology adopted in several studies (Assaf et al., 2013, 2015; Hassanain et al., 2014a, b; Sha’ar et al., 2017). The identified 20 causes for DDDs have undergone 10 initial quality checks through the interviews, and then pilot-testing, before being assessed by the domain specialists. The participants were asked to assess the causes of DDDs. Once the responses were received the following formula (Dominowski, 1980) was used to assign a significance index for each cause:

\[
\text{Significance index} = \frac{\sum_{i=0}^{4} a_i x_i}{4 \sum_{i=0}^{4} x_i} \times 100\%
\]

where \( i \) = response category, \( i = 0, 1, 2, 3, 4; a_i = \) responses given weight, \( i = 0, 1, 2, 3, 4; \) and \( x_i = \) frequency of \( i, i = 0, 1, 2, 3, 4; \)

- \( x_0 = \) frequency of “very high significance” response corresponding to \( a_0 = 4; \)
- \( x_1 = \) frequency of “high significance” response corresponding to \( a_1 = 3; \)
- \( x_2 = \) frequency of “significant” response corresponding to \( a_2 = 2; \)
- \( x_3 = \) frequency of “low significance” response corresponding to \( a_3 = 1; \) and
- \( x_4 = \) frequency of “not significant” response corresponding to \( a_4 = 0. \)

The significance index was categorized based on the scale depicted below (Juaim and Hassanain, 2011):

- if the index value is below 12.5 percent, then the cause is “Not Significant”;
- if the index value is between 12.5 and 37.5 percent, then the cause has “Low Significance”;
- if the index value is between 37.5 and 62.5, then the cause is “Significant”;
- if the index value is between 62.5 and 87.5 percent, then the cause has “High Significance”; and
- if the index value is above 87.5 percent, then the cause has “Very High Significance.”

The mean and standard deviation equations are shown below (Field, 2013):

The mean \( (\bar{X}) = \frac{\sum_{i=1}^{n} x_i}{n} \)

The standard deviation \( (S) = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{X})^2}{n-1}} \)

where \( i = \) response category, \( i = 0, 1, 2, 3, 4; \bar{x} = \) represents mean of responses; \( x_i = \) frequency of \( i, i = 0, 1, 2, 3, 4; \) and \( n = \) number of responses.

Findings and analysis

Table I presents the 20 identified causes categorized under their respective groups, along with their significance index, significance level, in-group ranking, overall ranking, mean, and standard deviation. The significance index was computed to determine the in-group and overall ranking of each of the identified causes of DDDs. The in-group ranking was used to assess the relative significance of a given cause, with respect to other causes under the same category. These computations have facilitated the identification of the causes that had the
most significant role in each organization (i.e. design firms and owners). The overall ranking was used to assess the relative significance of a given cause, with respect to all the identified causes, regardless of the category. This facilitated the identification of the parties most responsible for the causes of DDDs.

The mean together with the standard deviation was used to assess the dispersion of the assessment among the respondents. An examination of the standard deviation indicates a small dispersion among the responses from the professionals.

Causes pertaining to staff at the design office

This category has five causes, as presented in Table I. The cause “the level and quality of the design professional’s education” received the highest rank in this group, having a significance index of 74 percent, with a “High Significance” rating. The reason for this could be not so much due to the quality of education, but due to the lack of job-specific technical skills. It is common for major organizations to enroll entry-level employees in an orientation program before assuming more important roles. This view was also voiced by Slater and Radford (2012) who on conducting a survey found that the majority of the respondents were of the opinion that architectural graduates were ill-prepared for the construction industry. In Dosumu et al. (2017), consultants considered “designer professional education” among the main causes of errors in construction contract documents. On the other hand, “overreliance on software tools” was deemed by consultants to be a relatively less significant cause of DDDs, receiving a significance index of 56 percent and a significance level of “Significant.” This may be attributed to the practice of presenting the outputs obtained from the software
tools without possessing a clear understanding of the implications of the outputs obtained. With regards to previous studies, this finding contradicted Love et al. (2006) who found that, overall, “ineffective use of information technologies” was ranked as the most significant cause of rework for the design team.

**Causes pertaining to the composition of the design team**

Table I provides the rankings of the three causes under this category. Consultants considered “team members’ communication skills” as the most significant cause of DDDs, with a significance index of 75 percent and a significance level of “High Significance.” Although individuals might possess excellent interpersonal skills, language barriers due to diverse nationalities might render these skills as ineffective. Supporting this finding was the study by Dosumu and Iyagba (2013), where communication was viewed by the participants to be among the causes responsible for errors in construction documents. The least significant cause in this group was “design team cohesiveness,” with a significant index of 63 percent, and a significance level of “High significance.” Despite the “High Significance” level of this cause, it was considered not as severe as “team members’ communication skills.” It is highly likely that there is a correlation between the former and the latter cause in that language barriers and cultural differences may impede the ability of individuals to form stronger bonds just as they prevent proper communication.

**Causes pertaining the design management of the project**

Table I displays the rankings of the nine causes under this category. With a significance index of 76 percent, and a significance level of “High Significance,” “assigning design tasks to designers who lack work experience” was ranked as the most significant cause of DDDs in this category. This could be attributed to the practice of some design firms seeking less experienced personnel due to lower salary demands. With respect to other studies, in Nigeria, Sunday and Afolarin (2013) found that the primary cause of error in construction documents was “professional’s inexperience.” Similarly, in another study by Dosumu and Iyagba (2013), also in Nigeria, the consultants viewed “designer experience” as among the most significant causes of DDDs. At the opposite end of the list, “accepting low design fee” was ranked as the least significant cause, obtaining a significance index of 54 percent and a significance level of “Significant.” According to this finding, it would seem that clients are aware of the correlation that exists between the design fee level and the quality of the design work, and thus, strive to offer designers reasonable fees. This finding was in conflict with that of Dosumu and Iyagba (2013) where the consultants saw “insufficient fund to create quality document” as being among the major causes contributing to DDDs. More surprisingly, the finding also did not agree with Darwish’s (2005) study, based in Saudi Arabia, where the consultants viewed “Low fee structures” as the most frequent cause of DDDs. This seems to suggest that there has been an improvement in the way design fees are determined over the past decade, perhaps due to an increase in awareness of the significance of the design stage to the project’s life cost.

**Causes pertaining to the client’s involvement in the project**

Shown in Table I are the rankings of the three causes under this category. As was observed in the “causes pertaining to the composition of the design team,” a cause relating to communication appears as the most significant cause, namely, “designer misinterpretation or failure to understand client’s intent.” This cause received a significance index of 62 percent, corresponding to a significance level of “High Significance.” Similar to “causes pertaining to the composition of the design team” category, it may be assumed that language barriers could be a reason for this cause being ranked as the most significant cause. As for the least
significant cause, “client experience” was observed to be the least significant, obtaining a significance index of 56 percent with a significance level of “Significant.” This agrees with the observation made in the “causes pertaining the design management of the project” category where “accepting low design fee” was the least significant cause. In particular, this finding illustrates the relationship of the two causes whereby clients who are more experienced will be less prone to offer low fees, and hence designers are not under pressure to accept low design fees.

Discussion
In light of considering all the causes, the top most important cause contributing to DDDs was “assigning design tasks to designers who lack work experience” (76 percent). It worth mentioning that the result obtained for this could be attributed to consultants’ desire to further increase their profit margins, and not because of falling under financial pressure. The next top causes were “team members’ communication skills” (75 percent), “the level and quality of the design professional’s education” (74 percent), “cross-disciplinary coordination” (74 percent), “effective design team” (70 percent), and “lack of knowledge transfer mechanism” (70 percent).

The causes that were ranked relatively low by consultants were “change in staff during the project,” “overreliance on software tools,” “designers engaging in simultaneous work,” “reuse of construction specifications and design details,” “use of timeboxing to complete design tasks,” “accepting low design fee,” “designer’s failure to understand client’s intent,” “unrealistic client demands,” and “client experience.” It appears that since the issue of “accepting low design fee” is not highly significant, “timeboxing,” “change in staff during the project,” “designers engaging in simultaneous work,” and “reuse of construction specifications and design details” which are a function of “accepting low design fee” are, as expected, not highly significant. Furthermore, reinforcing the previous observation that clients were not perceived as significant contributors to DDDs, two causes relating to the clients, namely, “client experience,” and “unrealistic client demands” were perceived as among the least significant causes contributing to DDDs. This also explains why “accepting low design fee” was not a major issue. If the client imposed unrealistic demands, the design consultant would have been forced to accept low fees, as a means of securing work in a bid to remain financially afloat.

Table II is a summary of the four major categories, displaying the average significance index, number of causes, and rank of each category. As presented in Table II, the category of causes pertaining to the composition of the design team received the highest average ranking of 63 percent. This finding encourages design firms to seriously consider improving the way their organizations operate. They must begin by directing their attention toward improving the composition of their teams. The category of causes pertaining to the client’s involvement in the project was perceived as the least significant category with an average significance index of 59 percent. This, as highlighted before, could be because clients understand they are required to pay a fee commensurate to the quality of work they expect to receive.

<table>
<thead>
<tr>
<th>Causes of design documents’ deficiencies</th>
<th>SI</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factors pertaining to staff at the design office</td>
<td>63</td>
<td>3</td>
</tr>
<tr>
<td>Factors pertaining to the composition of the design team</td>
<td>69</td>
<td>1</td>
</tr>
<tr>
<td>Factors pertaining the design management of the project</td>
<td>64</td>
<td>2</td>
</tr>
<tr>
<td>Factors pertaining to the client’s involvement in the project</td>
<td>59</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: SI, significance index
Design documentation, although being a narrow focus, plays a highly significant role in the successful development of a project. Any improvement in this early stage of a project should greatly enhance the performance of the entire project. Thus, it is in the authors’ view that, although being narrow, the topic of design documentation is of great importance to the construction industry, deserving more attention.

**Conclusions and recommendations**

This paper explored the key causes of DDDs in large construction projects based in Saudi Arabia. In total, 20 causes were identified from the literature. These causes were divided into four groups, namely, “causes pertaining to staff at the design office,” “causes pertaining to the composition of the design team,” “causes pertaining to the design management of the project,” and “causes pertaining to the client’s involvement in the project.” The causes that share a common theme were clustered together in one group. The 10 professionals (through interviews as well as pilot-testing) who reviewed them were in agreement of the classification of the 20 causes under their respective groups. None of the identified causes were ranked lower than significant (i.e. obtaining a significance index of less than 62.5 percent). The six most significant causes, in a descending order of significance, were “assigning design tasks to designers who lack work experience” (76 percent), “team members’ communication skills” (75 percent), “the level and quality of the design professional’s education” (74 percent), “cross-disciplinary coordination” (74 percent), “effective design team” (70 percent), and “lack of knowledge transfer mechanism” (70 percent).

The causes that received relatively low scores were “designer’s failure to understand client’s intent” (62 percent), “unrealistic client demands” (60 percent), “use of timeboxing to complete design tasks” (59 percent), “change in staff during the project” (57 percent), “overreliance on software tools” (56 percent), “designers engaging in simultaneous work” (56 percent), “reuse of construction specifications and design details” (56 percent), “client experience” (56 percent), and “accepting low design fee” (54 percent).

The research recommends the following measures to reduce the causes of DDDs in the construction industry in Saudi Arabia:

- Since it was concluded from the findings that designer’s education was insufficient for professional practice, the paper proposes that design firms should adopt the practice of enrolling their new employees to an intensive orientation program, establishing it as an industry standard practice across all organizations.
- Design firms should be more diligent in recruiting new employees to ensure that the best balance of different skill sets is achieved, including language proficiency as this was speculated as being a major impediment to proper communication and team cohesiveness.
- Design firms should apply great effort in documenting any instances of errors in design documents. The documentation should include information such as the error type, its frequency, the stage at which it occurs, and its potential causes. These lessons should then be incorporated into the training programs.
- The design firm should monitor the reoccurrence of these errors to evaluate the effectiveness of their countermeasures.
- Emphasis should be placed on the thoroughness of the design brief stage so as not to misinterpret client’s requirements.

The novelty of this study stems from increasing the level of awareness in the construction industry in Saudi Arabia about the causes of DDDs that adversely influence the effectiveness of the professional practice in design firms in Saudi Arabia. Thus, it is hoped that this research
has been able to provide a contribution to research and the industry, and will be of direct professional benefit to the different stakeholders in the construction industry, namely, project owners, design professionals, contractors, occupants, and facilities managers.

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The consideration of trees in rights of light cases Part 2

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Abstract

Purpose – The purpose of this paper is to continue the research set out in the consideration of trees in rights of light cases Part 1. To consider whether it is possible to measure a tree with sufficient accuracy that the impact on daylight within a building can be predicted in a way that can be applied in rights to light cases.

Design/methodology/approach – By reading published research on tree growth rates, crown transparency and theoretical modelling it is intended to determine the available methodologies for predicting light transmission through tree crowns. Then by inspecting common oak trees in all parts of the country, it is intended to review whether the available methodologies are capable of producing a relatively accurate result using manual methods or whether it is necessary to devise a software solution.

Findings – The research found that whilst theoretical methods exist for predicting light obstruction by trees, these could not be used in practice and that manual methodologies would not provide sufficient accuracy. However, survey techniques such as 3D Point Cloud can be taken further with the development of a software solution that uses an algorithm to predict branch size and location where these are not visible in a survey.

Research limitations/implications – This research concentrates on the theoretical aspect of assessing trees in rights to light cases. It is usually necessary for a live legal case to occur before research into software takes place. It will be necessary to develop the software and then test survey a tree in full leaf and in the absence of foliage to determine whether the algorithm is sufficiently accurate and this will take time.

Practical implications – This research concentrates on the theoretical aspect of assessing trees in rights to light cases. It is usually necessary for a live legal case to occur before research into software takes place and the conclusion reached was that it will be necessary to develop the software and then test survey a tree in full leaf and in the absence of foliage to determine whether an algorithm is sufficiently accurate and this will take time. It has also been demonstrated that trees may be considered as existing obstructions in rights to light cases and that once software has been developed and tested then it will enable developers to show that their proposals have less impact on the daylight within an adjoining property than would be the case if trees are ignored.

Social implications – In many instances, the economic development of a site, especially social housing, is limited by the rights to light of adjoining owners. Where it can be shown that the light levels enjoyed by those owners are already impaired by existing trees then this may assist the developer.

Originality/value – At this point no one else has researched this subject to the extent contained in this paper.

Keywords Software, Rights to light, Measurement of trees, Point cloud, Crown transparency

Paper type Research paper

Introduction

In the previous paper “The Consideration of Trees in Rights to Light Cases Part 1”, the case was made that trees have been ignored in rights of light cases for what were, ostensibly, practical reasons and that there is now no legal or practical reason why this practice should continue. This viewpoint is supported by Cooper (2015) in his paper entitled “Easements: The Right to Light and Trees” where it was argued that the use of modern technology makes it possible to accurately assess the impact of trees on daylight to a room in existing circumstances and that one of the implications of this could be that the effective damage that would be caused by a proposed development might be reduced significantly.

The aim of this paper is to consider whether it is possible to measure a tree or trees with sufficient accuracy that the impact on daylight within a building can be predicted in a way that can be applied in rights to light cases.
This paper builds on the previous by investigating the following key factors:

1. Whether the measurement of the obstruction caused by trees can be standardised. This is relevant because without a standard approach it would not be possible for the parties or a court to be satisfied as to the relative accuracy of any results.

2. Verification of standard tree crown transparency factors. The existing published results which are quoted by BRE amongst others have not been considered in the context of rights to light and are used as a theoretical adjustment factor in daylight for planning considerations. The calculations for planning purposes differ significantly from those for rights of light.

3. Whether annual tree growth rates can be confirmed. This paper explains below that it is necessary to consider the obstruction caused by the tree(s) at a date one year prior to the actual measurement and thus it is necessary to be able to evaluate the growth that will have occurred in the preceding year and to deduct this from any calculations.

4. Comparison of results produced by point cloud survey with predictions using the above. For the purposes of advising a court, it is essential that any theoretical calculations can be verified through actual measurement.

5. Development of software solutions. Ultimately any rights of light practitioner will need to have a tool that handles the necessary calculations and since most now use software based upon AutoCAD or other similar products it is necessary to ascertain whether it is possible to develop a software tool that will meet this requirement.

It was established in Part 1 that, in order to achieve a valid result, it is necessary to be able to measure the minimum obstruction provided by a tree or trees during the year preceding the date of assessment. The minimum level of obstruction relates to the fact that the law only recognises a permanent obstruction. In *Presland v. Bingham* (1889) 41 ChD 268, it was found that a fluctuating obstruction such as packing cases may not be an interruption. In addition, in *Bennison v. Cartwright* (1864) 5 B&S 1, it was found that the dominant owner had to be aware of and to acquiesce in the obstruction for at least one year prior to any action to constitute a valid obstruction within the meaning of the law.

If it is accepted that trees and specifically deciduous trees in this instance can constitute a permanent obstruction and that a dominant owner, by failing to take any action, is deemed to have acquiesced in that obstruction then it is necessary to be able to assess, accurately, the extent of that obstruction. However, it is recognised that no two trees are identical and, therefore, it may be necessary, if possible, to devise a methodology for the assessment of any tree or trees that may be applied from first principles.

Coniferous and other evergreen trees have limited transparency and significant variations in growth rates but, in terms of injury to the right to light, can largely be assessed by allowing solely for the growth that may have occurred within the year prior to assessment. Deciduous trees have significant variations in transparency as well as varying growth rates. Fortunately, the measurement of transparency is only necessary for the bare branch condition but to provide a basis for assessment at any time of the year it is necessary to understand the relationship between the crown size in full leaf and the transparency of the crown without of leaves.

**Methodology**

It is recognised that the organic nature of trees create wide varieties of shape and size as well as the differences between deciduous and evergreen trees. For the purposes of this research, it has been decided to concentrate specifically on one common deciduous tree for
which a considerable amount of research already exists in terms of measurement both of size and of daylight penetration.

To address the aim of this research, it is necessary, first, to review the available research literature to establish how trees have been measured as a different baseline measurement could lead to a different result; how growth rates are predicted; how consistent is transparency data, etc. From this it is possible to compare results with surveys undertaken on actual trees in various parts of the country in order to demonstrate validity.

Following on from this an attempt that is made to manually model the obstruction to light within a property, where a tree is positioned in front of a window, comparing the result achieved with that which would be expected based upon existing research. Using photographs of trees and superimposing the outline of a window, a pixel count was undertaken to determine, as a ratio, how many pixels showed sky and how many were obscured by branches. This ratio was compared to the transparency ratios quoted in BR209 by BRE and others. Consideration is then given to whether the result is capable of replication if the same tree is viewed from a different angle and also to multiple tree stands.

Finally, consideration was given to the current state of technology for modelling trees with degrees of accuracy where the gaming world has made great strides in realistic constructions and may have algorithms capable of predicting branch locations even when a tree is in full leaf.

Selection and consideration of the English Oak (Quercus Robur)

A number of tree types have been considered at various times of year but in order to formulate a baseline methodology it has been decided to assess only one type of deciduous tree, the English Oak, against the following variables:

1. Annual growth rates at different ages of tree and assuming average growing conditions, i.e. suitable soil and weather.
2. Method of measurement of trunk, crown, branch length, etc.
3. Transparency data comparing winter with summer and across a range of tree ages.
4. How does one measure the transparency of a group of trees?
5. Mathematical difference if branches are assessed as individual obstructions or if the tree crown is considered as a solid of reduced dimensions.

Annual growth rates of Quercus Robur

Research by Rogers et al. (2014) drawing on earlier research by McPherson et al. gives average ring widths of 2.294 mm and a range of growth rates based on core samples taken over 64 years of between 0.0011 and 0.00317 mm. In the context of rights of light calculations these amounts are very small and would probably not affect the results to a measurable extent. Their Table 2 at page 77 shows an average tree canopy (m) increment per year as 0.588 with a standard deviation of 0.43 but the point is made that growth rates are affected by the weather.

According to Gilman and Watson (1994) Quercus Robur can grow to a height from 50 to 60 feet, a spread from 40 to 60 feet, the crown uniformity is a symmetrical canopy with a regular (or smooth) outline and, according to them, individuals have more of less identical crown forms. It is noted, however, that this is an American publication and growth rates and uniformity could be expected to vary through factors such as climate and soil conditions. In other gardening publications in the UK the ultimate height is given as 100 feet or 30 metres with average growth of 9 inches or 23 centimetres per annum and in a publication by Dover District Council entitled “The English Oak” (2016) www.doverdistrictcouncil.com/the-english-oak/. It is said that the Oak
tree, “has a period of quite rapid growth for around 80-120 years and that is followed by a gradual slowing down. By the time the tree is 80 years old, it may well be over 20 inches (50 centimetres) in diameter. Acorns are not produced until the tree is about 25-40 years old […] and after about 250-350 years, the decline of the tree sets in, branches die back and the diameter growth slows right down”.

In the same publication by Rogers, Lawrence and Hutching’s, the average growth rates, plus standard deviation in brackets are given as average tree DBH increment in centimetres per annum is given as 0.228 (0.8), the average tree height increment in metres per annum is given as 0.601 (0.25) and the tree canopy increment in metres per annum is given as 0.588 (0.43). This research has been added to by Monteiro et al. (2017) in their paper entitled “growth rates of common urban trees in five cities in Great Britain (2017)”.

From all of this it is apparent that, to be able to assess the probable growth rate, it is necessary to ascertain the approximate age of the tree in the first instance and to consider environmental factors that might affect growth. In addition, the tree may have been cutback or have suffered die back but such things would be visible on inspection where they have occurred within the previous year.

In summary, therefore, it would be possible to estimate the amount of growth for a specific tree based upon its apparent age and condition.

Method of measurement of trunk, crown, branch length, etc.

Trees are not lollipops and from a subjective perspective they do not usually have a uniform shape and, therefore, it is important to have a methodology for measurement of the various parts of the tree that is sufficiently accurate.

At its simplest this could be to measure the trunk from the ground to the lowest branch as being the height of the trunk and the average diameter as being the width. The crown would be the spread of the outermost branches for width and the height from exposed trunk at the base to the topmost branches and branch length would be the extent of any branch having a girth exceeding 150 mm measured from the trunk to the point at which the girth reduces below 150 mm and this is the methodology employed in much of the published research. The rationale for the 150 mm girth is twofold in that the diameter would be approximately 50 mm and below this value the branch would be unlikely to register as an obstruction and smaller diameters are more prone to movement caused by wind making them less than permanent in nature.

More accurate assessments, using computer aided design techniques, create a polyline around the tree crown but it must be recognised that the outline of a tree crown to any point in a room may differ between adjacent points and that therefore the greatest accuracy would be achieved by dealing with the tree in three dimensions rather than two as occurs with traditional manual assessments using a Waldram diagram.

Survey technologies have progressed by leaps and bounds since the time when the Waldram diagrams were devised. The latest advancements include point cloud surveying which consists of a collection of data points defined by a given coordinates system. In a 3D coordinates system, for example, a point cloud may define the shape of some real or created physical system. Point clouds are used to create 3D meshes and other models used in 3D modelling for various fields including medical imaging, architecture, etc. In a 3D Cartesian coordinates system, a point is identified by three coordinates that, taken together, correlate to a precise point in space relative to a point of origin. x, y and z-axes extend in two directions and the coordinates identify the distance of the point from the intersection of the axes (0) and the direction of divergence, expressed as + or –.

In the field, 3D scanners gather point measurements from real-world objects for a point cloud that can then be translated to a 3D mesh or NURBS or CAD model. Thus, using point cloud surveying it is now possible, in the right circumstances, to create an accurate
three dimensional model of a tree at any point in time but, unfortunately, it is not always possible to use this technology when, for example, there is a need not to avoid requesting access to a neighbour’s land or, where it is used, it may not be possible to determine, from the model, the extent of branches forming the crown or even the height of the trunk when the tree is in full leaf.

Various traditional methods of measurement exist and the three basic parameters commonly measured to characterize the size of a single trunk tree are height, girth and crown spread. A detailed guideline to these basic measurements is provided in The Tree Measuring Guidelines of the Eastern Native Tree Society by Will Blozan. According to Blozan “tree height is the vertical distance between the base of the tree and the highest sprig at the top of the tree. The base of the tree is measured for both height and girth as being the elevation at which the pith of the tree intersects the ground surface beneath, or “where the acorn sprouted”.

When measuring tree heights from the ground the height can be calculated using the principle of similar triangles, a surveying technique taught to most scouts using a graduated pole. The second method uses a clinometer and tape and is commonly used in the forestry industry where the distance from the tree and angle of the clinometer are used to determine the height. Either of these two methods have the potential for significant errors including, for example, where the top of the tree is not visible from ground level.

The girth is a measurement taken as the distance around the trunk of a tree measured perpendicular to the axis of the trunk and the use of girth to arrive at an equivalent diameter is an older forestry measurement that is still used. The measurement is commonly taken at around 1.5 metres above ground level. Where there are significant low branches below this height, ignoring any minor sprouts and dead branches, then the girth is measured at the narrowest point below the lowest branch.

Crown spread is a measurement of the footprint or plan area of the crown of the tree expressed as a diameter. Naturally the spread is non-uniform and so it is usual to measure perpendicular axes and to take the average of the two measurements to calculate the crown spread. One useful tool for reviewing crown spread and changes over time is to use Google Earth and the built in measurement tools.

Research by Frank (2010) established a methodology for plotting different tree shapes graphically using ternary plot diagrams (see Figure 1). Using this methodology, he assessed the ratio of height to girth to average crown spread and plotted these on the chart below where he gave the measurement data for 140 live oaks measured as part of the NTS Live Oak Project.

**Figure 1.**
Tree shape diagram for live oak

*Source:* Frank (2010)
This diagram shows a reasonably tight cluster and Frank reported that “The height proportion exhibits a maximum of 17.23% of the shape value and a minimum of 6.55%, the girth (minimum of 19 feet in the data set) exhibits a maximum of 58.25% and a minimum of 40.25%, and Average Crown Spread maximum of 49.08% and a minimum of 30.92%.” It is noted that while the data set contains both multiple trunk trees and single trunk trees, both plot within the same tight cluster. It is possible, therefore, to conclude that any two measurements could be used to predict the third with a reasonable degree of accuracy.

By visiting a number of locations throughout the UK during 2015 to 2017, the author was able to verify the data to an acceptable degree of accuracy in healthy trees concluding that tree age and whether or not the tree had branches trimmed at some point did not appear to affect the ratio to any significant degree. It was noted, however, that the transparency was increased, as would be expected, where branches had been thinned. Some trees that were assessed had suffered damage through storms, etc., and these tended to sit outside the cluster.

In 2014, an assessment of the use of a hand-held camera for individual-tree 3D mapping in forest sample plots was undertaken (Liang et al.). It was established that using a terrestrial point cloud generated utilising an uncalibrated hand-held consumer camera at a plot level and measuring the plot at an individual-tree level and then identifying individual-tree stems in the plot and modelling these from the image-based point cloud and estimating the diameter-at-breast-height (DBH) of each tree, the detected-results could be compared with field measurements and with those derived from the single-scan terrestrial laser scanning (TLS) data. The experiment showed that the mapping accuracy was 88 per cent and the root mean squared error of DBH estimates of individual trees was 2.39 cm, which is acceptable for practical applications and was similar to the results achieved using TLS. The main advantages of the image-based point cloud data lie in the low cost of the equipment required for the data collection, the simple and fast field measurements and the automated data processing. The disadvantages of the image-based point cloud data include the limited capability of mapping small trees and complex forest stands.

In conclusion, therefore, there are a number of ways in which the size of a tree may be assessed or estimated ranging from simple geometry and using the data referenced above, through to a full LiDAR/point cloud survey. The level of accuracy will vary with methodology but this should be no worse than the levels of accuracy achieved using traditional Waldram methodologies (Defoe and Frame, 2005).

Transparency data comparing winter with summer and across a range of tree ages
Data published by the BRE in BR209 does not specify whether the transparency varies with the age of the tree although research by Yates and McKennan (1989) and Wilkinson et al. (1991) suggest that the data sets used are based upon trees in the 12–14 metre range. The important aspect is that any new methodology will require the ability to be able to measure a tree crown at any time of the year and to predict the transparency of that tree in its leafless condition for the purposes of assessing what the permanent obstruction would amount to.

The light attenuation for Quercus using their methods was given as 47.81 ± 1.65 in winter and between 82.35 ± 2.05 and 84.78 ± 1.42 in summer, whereas the BR209 gives the figures as transparencies of 20 per cent in summer and 55 per cent in winter although not all leaves had fallen. The research by Nowak (1996) mapping with a telescoping measuring rod at crown boundary points every 1.5 metres vertically and at every 45° azimuth radially to map the crown shape gave a shading factor for Quercus Robur of 0.81 in full leaf. On this basis, it is reasonable to accept that, on average, the tree crown will intercept 45 per cent of the light from the sky passing through the crown during the winter and around 80 per cent when in full leaf, as a standard for assessment.
Bearing this in mind, a single tree may not block sufficient light, on a permanent basis, to significantly alter the so-called “grumble line” in a room which is currently set at 0.2 per cent using the Waldram diagram (Defoe and Frame, 2005). However, it is quite common for trees to exist in groups and for this reason it is necessary, therefore, to consider how a group of trees might affect the light within a room where the trunk and/or crowns overlap when viewed from within the room in the manner of the Waldram methodology.

How does one measure the transparency of a group of trees?

It may be perceived that a group of trees in close proximity would inevitably block more of the visible sky than a single tree. However, Oak trees are rarely planted in uniform rows and the degree of overlap will vary considerably for a wide range of situations. In addition, the effect of perspective when the trees are viewed from worktop level within a room means that where trees are further from the viewpoint their crown will be relatively lower and the value of obstruction based on the Waldram diagram would be commensurately lower.

In Figure 2(a) and (b), to the left is a single tree and to the right the same tree viewed from a different aspect with other similar trees behind. The rectangles in each image represent windows of view from within a room and clearly demonstrate the difference in obstruction that results from several trees one behind the other. It also shows how the different perspective results in tree crowns further away from the viewpoint which appear lower and thus obscure sky visibility that would previously have been available either side of the trunk.

Where the crowns overlap the apparent transparency will reduce through the combined effect but there is no current published research on this and having compared numerous

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**Figure 2.**

Oak tree viewed from different angles
situations it is apparent that the number of variables is a significant problem. For example, the trees when viewed from a point within a room may be at different separations, be of different heights and different crown spreads as well as being in different alignments from any specific viewpoint to the next. In this example, using a manual Waldram diagram to assess the visible sky component, with the single tree acting as an obstruction, the sky component equates to approximately 3.3 per cent of the sky dome. Whereas for the group, the sky component equates to approximately 1.8 per cent of the sky dome. Even the slightest change in viewpoint would produce a different result.

It is not possible, therefore, to avoid the conclusion that it is only by accurate modelling, based on a point cloud survey, that it will be possible to accurately assess the combined impact of a stand of trees.

*Mathematical difference if branches are assessed as individual obstructions or if the tree crown is considered as a solid of reduced dimensions*

It is important to understand whether, if it were possible to make manual assessments of trees as obstructions, there would be a mathematical difference between considering the tree crown as individual branch obstructions or as a solid based upon an assessment of the total volume of the branches. From a practitioner perspective, it is often necessary to be able to simplify the modelling even when creating an electronic model but more especially when using traditional means.

The conclusion that has been reached regarding modelling of stands of trees would appear to preclude the use of manual methods in these instances but notwithstanding this it is necessary to consider whether a single tree might be modelled using traditional means and if so could this be achieved by converting the mass of branches into a single solid obstruction.

By using the tree image in Figure 2(a) and counting pixels as illustrated below in Figure 3, it is possible to estimate the sky visibility and obstruction. If the BRE transparency of 55 per cent could be applied then pixel counting should show that 55 per cent of the area of the image should be free from obstruction but, in fact, the pixel count shows that 1,025 out of 3,528 are unobstructed which equates to just over 29 per cent.

This image was selected at random from a considerable number of photographs taken during winter months. The issue is that it concentrates on one section of the tree rather than the whole crown, as would happen when it is viewed through a window, and thus, whilst the tree crown, as a whole, may approximate to the BRE guidance in terms of transparency,
the actual transparency when viewed from within a room will depend upon the part of the
tree that is visible from any specific point, through the window.

Therefore, from a practitioner perspective, it will be necessary to first take an image such
as the above and consolidate the branch obstruction into one mass, but this again raises
another issue. Where on the diagram should the mass be positioned and what shape would
be appropriate? In fact, the number of variable is too great to create as useable algorithm.
The Waldram type diagram gives different values to each part of the diagram and so, for
example, bringing the mass of the branches to each side into the centre would change the
value of the obstruction. It is not possible to come to any conclusion other than that it is not
possible to model a tree crown with any acceptable level of accuracy other than by using the
electronic survey techniques described above.

**Development of software solutions**
This paper has demonstrated that it is possible to measure a tree or trees in terms of height
and crown spread and to estimate with a reasonable degree of accuracy what the growth
will have been in the previous year, but it has also demonstrated that manual methods
of assessment of the light obstruction by trees cannot be undertaken with any degree of
accuracy. However, survey techniques using 3D Laser Point Cloud can produce an accurate
model that may be used within a computer programme that assesses light injury within the
AutoCAD or REVIT environment (other software does exist but is not yet commercially
available). The issue to be resolved is that the survey may be undertaken at any
point during the year when a potential cause of action arises but for the purposes of rights to
light calculations the model should be based upon the least foliage being on the tree, as
previously explained.

Currently, when using a point cloud survey, the data are imported into AutoCAD and
converted to a useable format for the model but there is no separate application that would
allow the user to easily remove leaves from the tree model to expose the trunk and branches.
Wang et al. (2013), in describing how trees can be modelled in virtual reality, have described
how it may be possible to effectively reverse engineer a tree in leaf to one without leaves.

They identified nine sub-problems to describe the issues and their corresponding
approaches:

1. 3D laser point cloud reorganisation;
2. tree segmentation or classification;
3. skeleton point connection of discontinuous branches caused by occlusion from other
   branches or leaves;
4. twigs skeleton synthesis;
5. skeleton estimation of completely occluded branches;
6. branch cross-section radius calculation;
7. leaf shape, foliage location and density estimation;
8. phyllotaxis reconstruction; and
9. branch ridges and collars reconstruction.

For the purposes of rights to light it is only necessary to consider 1, 3, 5 and 6.

**Reorganisation**
Wang et al. stated that point cloud data can contain tens of billions of discrete scattered
points and that the segmentation algorithm from such a large amount of data is time
consuming and, thus, the need for reorganisation is inevitable. They identified that, whilst more research is required, the use of the multi-dimensional binary search tree, i.e. k-d tree could be developed.

**Skeleton construction**

This process consists of two parts, first, the skeleton extraction itself and, second, the branch radius estimation. In reviewing trees without leaves they concluded that the whole point cloud of branch surface is necessary when using level sets and thus the scan should be from multiple angles. Continuing to look at trees with partial occlusion by leaves they described how major branches could still be visible in part but that twigs and smaller branches would be inadequately sampled in the survey and, so they suggested that triangle similarity might be used. In addition, they examined the benefit of angle range judgement and particle flows to estimate the skeleton and found that the particle flow trace using two images taken from different angles of a given tree produced a reasonable representation.

Where trees are in full leaf the crown is obscured but they argue that, whichever way it grows, its surface is constructed by cloud in the form of a cylinder and the algorithm of the middle axis proposed by Marek and Teller (1998) to form the middle line of the crown surface could be used to construct the skeleton.

**Branch radius estimation**

Leonardo Da Vinci surmised in the 15th century that all the branches of a tree at every stage in its height, when put together, are of equal thickness to the trunk. This was supported much later by Shonzaki and West in their discussion of the pipe model and then proposed the WBE model (West et al., 1999). The WBE model is a fractal like network that describes the vessels and tracheid between main and subsidiary branches. They further described how the relationship between branches could be predicted by assuming that the ratio between the child and parent radii is taken to be proportional to the ratio of the supported lengths for the child and parent raised to the \( \frac{3}{2} \) power or that the ratio between one of the children and parent radii is taken to be proportional to the ratio of supported lengths for the child and the sum of all the children raised to the \( \frac{1}{2.49} \) power.

When using these concepts for the purposes of rights to light calculations it is apparent that with a full multi-point survey, and from the evidence demonstrated in the appended photographs (see the Appendix) that it will be possible to pick up parts of branches when a tree is in full leaf and using an algorithm based upon the concepts described above, to extrapolate the likely branch layout with a reasonable degree of confidence. Smaller twigs are not so critical as they will make little mathematical difference to the resulting sky visibility.

**Conclusion**

In this second paper, the aim was to investigate the following:

1. whether the measurement of the obstruction caused by trees can be standardised;
2. verification of standard tree crown transparency factors;
3. whether annual tree growth rates can be confirmed;
4. comparison of results produced by point cloud survey with predictions using the above; and
5. development of software solutions.
Whether the measurement of the obstruction caused by trees can be standardised

It is an accepted fact that the courts will weigh the advice of any expert in the field of rights to light, on the basis of agreement between experts as to the methodology of measurement and to this end it will require a standardised approach in exactly the way that occurred through the original work of Percy Waldram (1909b).

In order to understand whether it is possible to have a standardised approach to measurement, it was decided to, so far as was possible, research a single tree type (Quercus Robur) and to assess whether the following variables could be defined sufficiently that a computer programme could be used to predict the impact on daylight within a room:

1. Annual growth rates at different ages of tree and assuming average growing conditions, i.e. suitable soil and weather.
2. Method of measurement of trunk, crown, branch length, etc.
3. Transparency data comparing winter with summer and across a range of tree ages.
4. How does one measure the transparency of a group of trees?
5. Mathematical difference if branches are assessed as individual obstructions or if the tree crown is considered as a solid of reduced dimensions.

This research has discovered that growth rates are reasonably predictable but have little impact on the final results; similarly, the methods of measurement of the parts of tree have already been standardised for other purposes. Transparency data have been shown to be of little use as it is not possible confirm that the transparency ratio works for just the part of the tree that is visible from within the room and thus, where a stand of trees is concerned, the results would be even more unreliable. It has also been demonstrated that converting the mass of branches to a single mass for calculation purposes would not be a practical solution.

On this basis, it is necessary, if one wishes to achieve a standard methodology for measurement to consider how this may be approached using modern technology.

Verification of standard tree crown transparency factors

The existing published results, which are quoted by BRE amongst others, have not been considered in the context of rights to light and are used as a theoretical adjustment factor in daylight for planning considerations. The calculations for planning purposes differ significantly from those for rights of light and to this end it was necessary to understand whether the transparency factors are sufficiently close to reality and whether they may be used for rights to light purposes albeit by using different algorithms for the final analysis.

What this research discovered was that the transparency factors may be correct when considering a whole tree but that they cannot be used when considering just the part(s) of a tree that may be visible through a window. Thus, even when using modern technology, it would probably not be possible to apply a single adjustment factor to any algorithm.

Whether annual tree growth rates can be confirmed

It has been explained that it is necessary to consider the obstruction caused by the tree(s) at a date one year prior to the actual measurement and, thus, it is necessary to be able to evaluate the growth that will have occurred in the preceding year and to deduct this from any calculations.

From extensive research with the Forestry Commission and others it has been possible to confirm that growth rates are predictable and within a relatively small range and, in fact, this research has demonstrated that the growth rate of Quercus Robur is sufficiently slow
that the changes in any one year are probably insufficient to affect the results. In this regard, any modern technology would probably not require an adjustment factor unless considering a tree type that has a greater growth rate as occurs with some coniferous trees.

**Comparison of results produced by point cloud survey with predictions using the above**

For the purposes of advising a court, it is essential that any theoretical calculations can be verified through actual measurement. One of the main difficulties associated with tree measurement is that, for rights of light purposes, it is necessary to assess the tree with minimum foliage, but the timing of any assessment might not coincide with this condition. It has been shown that published data on tree crown transparency are not reliable for this type of calculation and it has been demonstrated that it is not possible to equate the mass of individual branches with a single mass as the Waldram Methodology weights an obstruction according to the position of that obstruction on the diagram.

This research has shown, from a theoretical perspective, that the obstruction values could be assessed manually, e.g. by using photographs to assess where the branches are and drawing up individual Waldram diagrams from a series of viewpoints within the room, but that, from a practical perspective, this would prove far too labour intensive to be economical. By comparison, it is possible to undertake the survey of the tree(s) using point cloud technology and that when the survey is undertaken with the tree(s) in minimum foliage conditions the results would be expected to have measurably greater accuracy.

The weakness that exists is in the timing because when a tree is in full leaf the point cloud survey will produce a complex set of data that would have to be interpreted so that the leaves are removed from the final model and whilst this could be done manually it would, at present, be very labour intensive. A software solution is, therefore, very desirable.

**Development of software solutions**

Ultimately any rights of light practitioner will need to have a tool that handles the necessary calculations and since most now use software based upon AutoCAD or other comparable products it is necessary to ascertain whether it is possible to develop a software tool that will meet this requirement and to this end it appears possible that a software solution may be viable in the near future. The accuracy of any output from the software will depend upon the ability to undertake a full point cloud survey from as many directions as possible and, if the survey is undertaken whilst the trees are in leaf then an algorithm will be required that takes the available evidence and extrapolates branch size and location whilst removing the foliage from the data.

The challenge will be for the software providers to develop the solution in the absence of a driver such as a live case requiring the assessment.

**References**


Further reading


Defoe, P.S. (2008a), The Validity of Daylight Calculations in Rights of Light Cases, Thesis Anglia Ruskin University, Chelmsford.


(The Appendix follows overleaf.)
Appendix

Plate A1.
Photographs of trees showing how branch structure is visible even when trees are in full leaf

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