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TABLE OF CONTENTS

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Korean Academic Librarians' Recognition of the High Density Book Storage System

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ABSTRACT

Korean academic libraries are facing a serious space shortage problem due to the inability to uphold the rapidly increasing amount of printed materials despite having expanded the number of physical facilities. Data computerization has been considered as a solution to the issue, but deliberation for the High Density Book Storage System has been on the rise because of its impressive method of preserving printed materials in a realistic facility. Despite the different methods of print material storage, Korean academic libraries have largely focused on investing in the least efficient method of compact shelving to solve this issue. It is hypothesized that the misuse of funds on inefficient systems is occurring due to the lack of knowledge about the high-density book storage systems like the Harvard model. In order to propose a realistic solution to the academic library space shortage crisis on a logical basis, it is imperative that a study of academic librarians is conducted to investigate their knowledge on such efficient storage systems.

Keywords: Space Shortage Problem; Academic Library Facility; High Density Book Storage; Harvard Model

1. Introduction

Korea's rapid economic grown in the 1980s brought enormous spatial expansion to the physical facilities associated with academic libraries. The growth allowed for a new era in establishment of modern Korean academic libraries and fostered a positive impact on collegiate environments nationwide. Beginning in 1955 with only 43 total public and private academic libraries in the entire country, Korea reached a total of 523 facilities in 2009.

More importantly, there was a noticeable increase in book quantity. With 1,297,034 books observed in Korean academic libraries in 1955, the number was registered at 121,479,083 by 2009 [1]. **Figure 1** presents the rapid growth curve of printed materials observed in academic libraries from year 1955 to 2009. **Table 1** shows the comparison of number of books, academic library facilities, and librarians between 1955 and 2009 in Korea. The total of amount of books had expanded by 9370%, and that increase was almost 8 times faster than the growth of academic library facilities. This exponential growth created a serious space shortage problem for all Korean academic libraries and slowly led to academic environment degradation. **Figure 2** represents the problem graphically.

The vastly increasing quantities of printed materials and the library space shortages brought about by it are the biggest problems facing current academic libraries in Korea. Korean academic libraries have been in search of efficient book storage systems to solve the issue. The movable compact shelving unit, also referred to as the 'mobile rack', is widely utilized. Since the adoption of the movable compact shelving system, open access systems have been put in place. The open access system provides higher service quality for its users, but it is limited in space efficiency. The alternative closed access system lacks a user-friendly operating system; however, it has much higher space efficiency at a significantly lower cost. Judging by the cost-benefit tradeoff, the closed access high-density book storage system is the only logical option to resolve the academic libraries' space shortage crisis [2].

The study was projected to assess Korean librarians' understanding of high-density book storage facilities used for academic and research purposes, and identify

Table 1. Number of academic library facilities, books, and librarians in 1955/2009.

Year	1955	2009
Academic Libraries	43	523
Books	1,297,034	121,479,083
Librarians	207	3686

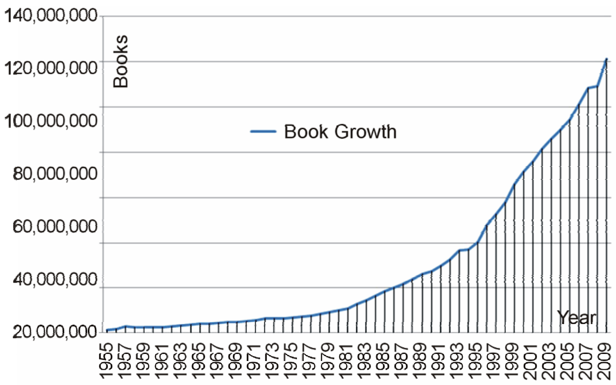

Figure 1. Book accumulation of academic libraries in Korea.

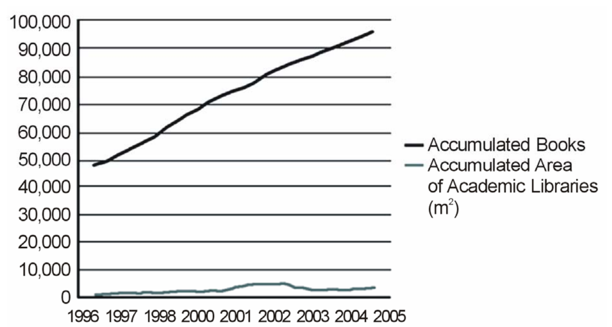

Figure 2. Comparison of book growth to library facility growth [3].

reasons for the lack of establishment of such facilities in Korea. The analysis of the survey responses will serve as a method to further resolve the space shortage crisis in a workable fashion.

2. High Density Book Storage: Harvard Model

In the 90's, Harvard began its construction of high density book storages, the "Harvard Model", as an efficient method of preserving low use print materials to serve as the solution for the space shortage problems in academic libraries. The Harvard Model provides extremely high space efficiency at a low cost. The original idea for this system was inspired by the distribution and warehouse industry. This system has spread all over the world and has now become a development standard for book storage facilities [4]. **Figure 3** shows the shelving system of Harvard Model at Rice University Library Service Center. More than 100 high-density book storage facilities have been built worldwide, 73 of those located just in the United States.

However, it has been found that Korean academic librarians have a definite preference for open access systems and there have not been any Harvard model storages constructed in Korea. An overwhelming majority of librarians continue to prefer expensive library buildings in lieu of low cost storage facilities despite the fact that new open access library facilities will never resolve space shortage problems. Many libraries have installed movable compact shelving units or remodeled their facilities to further accommodate, but these methods only postpone the impacts of the space shortage problem. These libraries inevitably face the same space shortage problems just after a couple of years after the completion of such constructions [5].

3. Survey Questionnaires & Evaluation

Previous surveys show that Korean academic librarians have acknowledged the need for high-density book storage systems in order to resolve space shortage problems. It is proposed that these librarians continue to solely utilize the movable compact shelving system, the mobile rack, with the exception of Sungkyul University's ASRS (Automated storage and retrieval system), because of their lack of understanding of high density book storage systems to make an informed decision on selecting the most efficient storage methods. As librarians are the most important individuals when making decisions on new constructions, remodeling projects, and operation systems of their respective academic libraries, it is important to investigate librarians' understanding of the high density book storage systems and their knowledge of opportunities to resolve space shortage problems.

Figure 3. Harvard model storage system at Rice University.

Questionnaires regarding the issue above were distributed to 463 academic librarians through email. Replies were received through "Google Drive" from 75 librarians at 169 universities in Korea from June 10-16, 2011. The same questionnaires were sent to another 1186 academic librarians at accredited 4-year universities resulting in 182 replies throughout a period from June 26th through June 30th, 2011. The questionnaires resulted in a response rate of 15.5% and a total of 257 responses.

The survey was comprised by 7 questionnaires as below:

- The necessity for the adoption of high density book storage systems to resolve the space shortage problem
- Knowledge about high density book storage types and operational options
- Critical decision making elements on library facility development
- Preferred methods of obtaining extra space to preserve printed materials
- Application plans for any possible available space
- Plans of developing extra book storage space with the exception of building a new library
- Understanding of cooperative book storage facilities

3.1. How Effective Do You Believe the High Density Book Storage System Will Be in Reducing the Space Shortage in Your Library?

The purpose of this question was to measure the librarians' opinion on the efficacy of high-density book storage systems in solving the space shortage issue. **Figure 4** represents the replies of this questionnaire. Out of 243 total replies, 159 (53%) and 100 (41%) responded that the high-density storage system would be very effective and effective, respectively. Judging from the data that shows a large majority, 94% of the responses, were positive for the implementation of high-density storage systems, it is concluded that most academic librarians are in favor of introducing this type of method into the nation's library system. From the small percentage of negative responses (1%), it can be said that there are hardly any opinions opposing high-density book storage systems. Those librarians who responded with a negative attitude towards this type of management system showed a lack of understanding of such systems and an extreme preference for open access management.

3.2. Choose All High Density Book Storage Types in Which You Are Familiar with the Method of Operation

This question was posed to librarians so that they would choose all types of high-density book storage systems in which they understood all facility and managing systems in order to investigate their level of understanding for each type of system. The survey result is shown in **Figure 5**. As expected, the compact shelving system (mobile-rack) received a large sum of 221 votes (91%) followed by the Automated Storage and Retrieval System (ASRS) with 93 votes (38%); however, only 4% of librarians identified as fully understanding the Harvard Model, in addition to a surprising 3% of librarians which stated that they had no understanding of high density book storages. It is inferred that Sungkyul University's 2010 construction of ASRS models helped in informing librarians about this specific method possibly resulting in the high number of votes for this system. It was unexpected that so many librarians, 34%, showed a high understanding for the outdated Multi-Tiered Stack Core System, but the result is interpreted as the librarians' informed knowledge about the history of librarians and their shelving systems.

The fact that Korean academic librarians have such limited knowledge about high-density book storages systems like the Harvard model, which has already become a standard in the United States and Europe, shows the librarians' lack of understanding is even far more limited than as previously predicted. The results of this survey show that it is imperative that further knowledge about this type of system is more widely distributed.

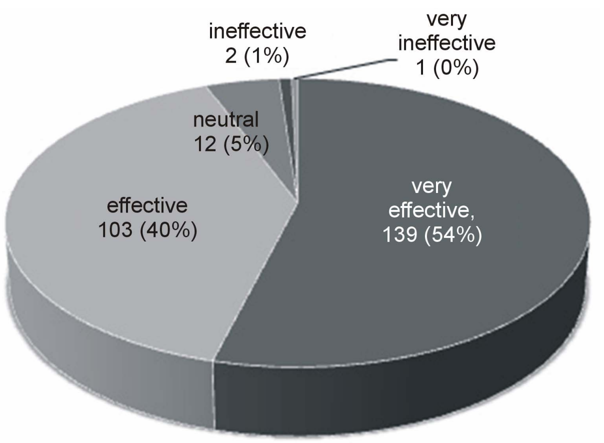

Figure 4. Necessity of high density book storage.

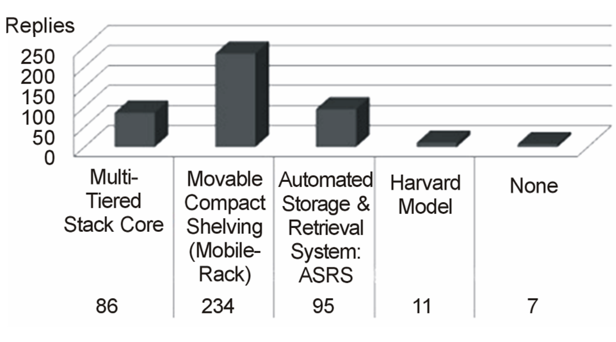

Figure 5. Awareness of high density book storage types.

3.3. What Is the Most Critical Element You Consider When Selecting a Book Storage Type?

The 66% of librarians replied that the book storage capacity per square footage, therefore space efficiency, was a critical element when selecting a storage type. This result is a strong representation of the magnitude of the academic library space shortage problem alongside the librarians' desire to resolve the issue. It signifies that spatial efficiency, rather than construction cost, should be deemed the highest priority when selecting a storage system. From the results, it can be inferred that librarians would prefer a facility with guaranteed space efficiency even with a trade off with time spent on budget collection compared to a shortsighted facility.

19% of the responses chose construction cost as seconding space efficiency in elements to be considered when choosing a storage facility. Difficulties in fulfilling a budget to construct a book storage system pushed opinions to prefer economical and practical facilities. A small minority of the responses chose options such as operational manpower (4%), operation and maintenance cost (5%), facility location (6%), showing that these other alternatives were far less critical compared to establishment cost and space efficiency. **Figure 6** shows the replies of this question. The Harvard Model is the most space efficient of the book storage systems with a low operation and maintenance cost needed for manpower in addition to low construction costs. Judging from the responses received from the pool of librarians surveyed, such systems that fully accommodate for all the considerations are the best options that should be introduced into the nation.

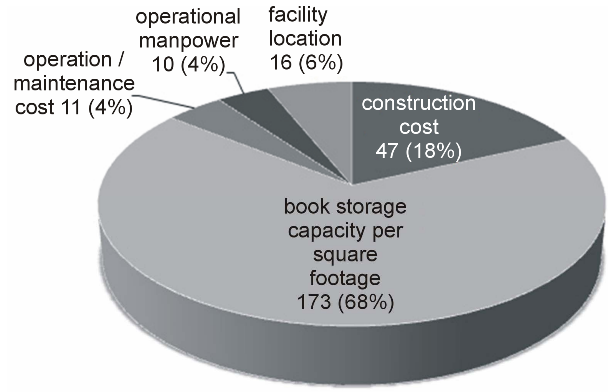

Figure 6. Critical decision element on storage type selection.

3.4. Which Option Is Best for Securing Extra Library Space? (Under Limited Budget)

Responses shown in **Figure 7** indicated that 40% of librarians' preferred storage options that are economical and better insure security of budget. However, large opinions showed that librarians still largely believed that at equal costs, they preferred open access to closed access services even if that meant less space efficiency (37%). It is thought that this is because when the questionnaire was formulated, the survey did not mention that open access storage systems preserved a mere 10% of what a high density book storage would under the same given square footage. Because librarians lack full understanding of the space efficiency potentials of the high-density book storage system, they still select the open access storage that matches the traditional library structure at a high percentage. Regardless of construction costs, librarians who supported the open access storage systems (15%) were relatively higher than those who supported the high density storage systems (9%), resulting in an overall 52% of votes preferring the open access system compared to the 47% that preferred the high density storage. It is inferred that the preference for the less efficient system is due to the insufficient understanding of the fairly new concept of high-density book storages. In addition, it can also be inferred that the librarians and other library staff that are under the constant stress of space shortage unquestioningly prefer the open access service because they aren't completely aware of the full import of the issue.

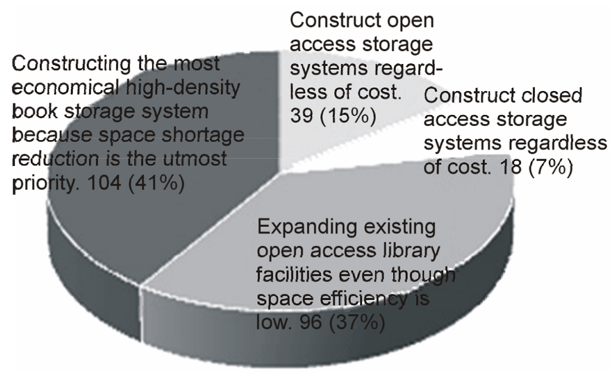

Figure 7. Options for securing extra space for library.

3.5. If It Were Possible to Transfer 500,000 Books to a New High Density Book Storage, What Would Be the Biggest Benefit to Your Library?

Improvements to shelving arrangements and operational convenience (52%) and the addition of a rest area to improve environmental quality (20%) were the top two potential usages of the new available space acquired from the implementation of the high-density book storage system. The opinions of librarians that believed that benefits brought about by an information commons and learning commons (12%) were important showed new up and coming trend of considerations for newly available space followed by the suggestion to add more reading space and open access shelving (10%), and adding space for new equipment for academic use (5%). **Figure 8** represents the librarians' opinion on the new available space usage.

Over half of the opinions stating that extra space should be used for better shelving arrangement provide evidence of the librarians' strong will to improve the spatial quality of the library. Furthermore, the other inclination to use space to add more resting areas shows the movement of librarians' ideology of "Library as a Place" [6], showing that economic growth naturally coincides with cultural development.

3.6. If You Could Not Secure a Budget for an Independent Library Facility, Which Do You Believe Is the Most Practical Plan among the Options Listed below?

For alternatives for obtaining book storage space, extension of closed access book storages received 39% of the votes, being the most preferred, followed by utilization of other existing facility (storage, basement, etc.) on campus at 29%, open access book storage extension with 13%; building rent for remote off campus book storages at 3% was found as a minority opinion. **Figure 9** shows the result of this questionnaire survey.

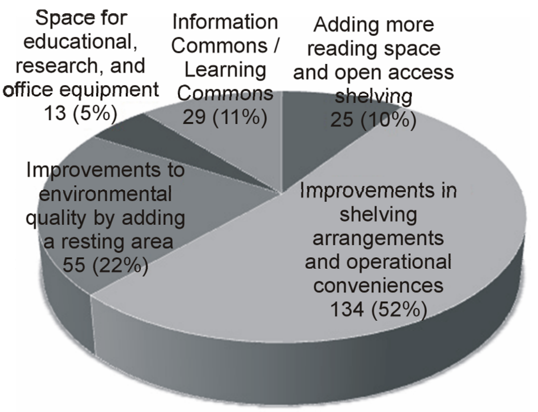

Figure 8. Potential usage of extra space provided by high density book storages.

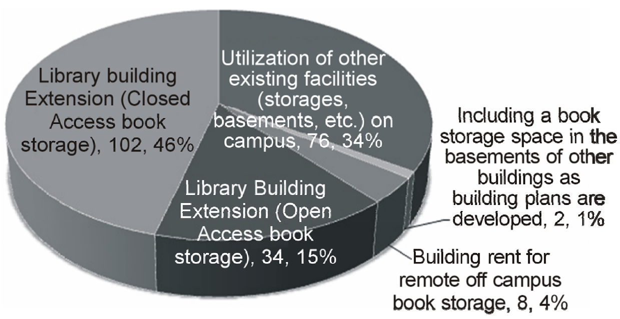

Figure 9. Alternatives to high density book storage.

Librarians showed no preference in including a book storage space in basements of developing buildings, albeit the option would allow for the implementation of a practical plan for maximum usage of real estate while providing a properly designed environment for book storage. It is probable that the idea of a basement brought about an image of a dark and humid environment with deficient ventilation that was negatively perceived as a good space for book storage; it is also possible that the librarians were displeased with the idea of storing books in a location other than a library.

Misconceived by those librarians, this alternative does not conceptualize an environment in which an already existing low quality basement is transformed into book storage. Rather, the option would allow for a new library facility to be constructed underground. If moisture control and appropriate ventilation were implemented, the benefits of an underground facility, including heat and sound insulation quality, protection from direct sunlight, and structural stability, would serve remarkably as book storage. The benefits of a basement facility are currently greatly underappreciated, thus resulting in this particular survey result.

3.7. What Do You Believe Is the Best Way to Accomplish a Cooperative Storage System in That Universities Come Together to Construct Book Storage under an Economical Budget?

Table 2 indicates the librarians' preference of the cooperative book storage. Librarians most preferred the cooperative book storage system that implemented joint ownership, joint management (35%). The options of preserving books together with separate ownership and separate management of a shared storage were voted with similar preferences (23% and 20%, respectively). Shared storages being built by the university with funding, but renting out the facility and having the cooperative storage stores and manages its own books without duplicates both resulted in 10% of the votes. Unique from the other surveys given thus far, this particular questionnaire presented with a tendency to present preferences for all options fairly consistently.

However, as a result of government oversight that induces extreme competitions amongst Korean universities, the goal of joint preservation, joint ownership, and joint management among these educational institutions will be a difficult target to meet. In consequence, joint construction of book storage with independent management will be the most realistic goal for Korean institutions.

4. Conclusion and Discussion

As concluded from the results of the full survey, the

Table 2. Preference of cooperative book storage types.

Cooperative Book Storage Types	No. of Replies (%)
Under agreement among all the institutions involved, establish a cooperative storage system under joint ownership and joint management and work to share data to preserve only single copies of printed material.	90 (35)
The cooperative storage owns and manages the facility and books independently, preserving single copies of all printed material	25 (10)
Under full agreement by the involved institutions, books are preserved together, but owned separately by respective universities	57 (23)
The storage is shared, but managed separately	56 (22)
Book storage is built by institution with funding and rented or co-managed by other institutions	25 (10)
Total	253 (100)

disuse of high density book facilities such as the Harvard Model that compose of 60% of American libraries and the overwhelming use of the movable compact shelving (mobile-rack) system by all Korean universities (with the exception of Sungkul University) signify Korean academic librarians' limited knowledge of high density book storage types and storage alternatives.

Considering the outstanding space efficiency and economic feasibility of high-density book storage systems, the questionnaires were returned with somewhat unexpected replies; however, such responses may be rationalized if the librarians answered the surveys with the thought of movable compact shelving in mind because of their lack of understanding of the high-density book storage types. Judging from the inadequate understanding of high-density book storage systems by librarians who are considered experts in the field of library management, it can be said that the public's awareness of such facilities is even more minimal.

Nevertheless, the librarians unanimously adhered to the idea that resolving space shortage problems was their primary priority and in order to meet that goal, facilities must have the outstanding space efficiency. Informing these experts with the strengths and weaknesses of various book storage types and then reconducting the surveys will ultimately result in meaningful changes to responses. Because there is no record of cooperative storage precedents in Korea, the responses regarding such facilities are seen to have resulted in more notional responses; however, it can be understood that work experience has naturally rooted understanding in our library experts.

This study was conducted to gauge Korean librarians' understanding of high-density book storage facilities widely used for academic and research purposes in highly developed countries and identify reasons why such storage systems were not constructed in Korea. The questionnaire serves as a measure of awareness of librarians on the library space shortage crisis. By analyzing the data retrieved from this survey, we can further work to resolve the space problem in a practical yet meaningful manner.

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A Multi-Criteria Decision Support System for the Selection of Low-Cost Green Building Materials and Components

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ABSTRACT

The necessity of having an effective computer-aided decision support system in the housing construction industry is rapidly growing alongside the demand for green buildings and green building products. Identifying and defining financially viable low-cost green building materials and components, just like selecting them, is a crucial exercise in subjectivity. With so many variables to consider, the task of evaluating such products can be complex and discouraging. Moreover, the existing mode for selecting and managing, often very large information associated with their impacts constrains decision-makers to perform a trade-off analysis that does not necessarily guarantee the most environmentally preferable material. This paper introduces the development of a multi-criteria decision support system (DSS) aimed at improving the understanding of the principles of best practices associated with the impacts of low-cost green building materials and components. The DSS presented in this paper is to provide designers with useful and explicit information that will aid informed decision-making in their choice of materials for low-cost green residential housing projects. The prototype MSDSS is developed using macro-in-excel, which is a fairly recent database management technique used for integrating data from multiple, often very large databases and other information sources. This model consists of a database to store different types of low-cost green materials with their corresponding attributes and performance characteristics. The DSS design is illustrated with particular emphasis on the development of the material selection data schema, and application of the Analytical Hierarchy Process (AHP) concept to a material selection problem. Details of the MSDSS model are also discussed including workflow of the data evaluation process. The prototype model has been developed with inputs elicited from domain experts and extensive literature review, and refined with feedback obtained from selected expert builder and developer companies. This paper further demonstrates the application of the prototype MSDSS for selecting the most appropriate low-cost green building material from among a list of several available options, and finally concludes the study with the associated potential benefits of the model to research and practice.

Keywords: Analytical Hierarchy Process (AHP); Decision Support System (DSS); Low-Cost Green Building Materials; Decision Analysis; Material Selection Factors

1. Introduction

As the green building movement begins to sweep through the housing construction industry, the application of cost effective and energy efficient building materials has become necessary in today's demanding economic market [1,2]. Recent discussions on the need to lower the growing demand for conventional sources of energy have highlighted the value of using low-cost green building materials and components, given their lower cost and energy requirements [3,4]. Evidence from previous studies has proven that implementing such products in construction has the potential to not only reduce health and environmental effects, but to also bring savings from energy, maintenance, and operational costs [5-9]. Yet, research has consistently shown that the patronage for such materials in housing construction is still at a very low level in comparison to many other conventional building materials [8,9]. Recent studies [10,11] argue that several attempts to adopt low-cost green building materials for housing design projects have generally been viewed as challenging, given that most designers are vaguely informed about the full life-cycle impacts of such products. They note that information relating to the impacts of such building materials in the housing construction sector appears to be less available, as evidence [11,12] indicates that only a small proportion of design and building professionals seem to have sufficient knowledge that could allow effective decision-making. Ashraf [11] and Zhou *et al*. [12,13] suggest that maximizing their potential use in the housing industry requires seamless access to appropriate informed information and full understanding of the various options available, so as to inform decision trade-offs at the design stage.

Despite the availability of accurate and reliable data, Seyfang [14] and Malanca [15] however, noted that most designers are found to make decisions regarding the selection of such materials on the basis of their past experience. They observed that inexperienced designers generally engage the traditional mode of selection, by relying on subjective individual perceptions of values and priorities in the material selection process, which rather than facilitate or drive their design ideas, appear to do the opposite thereby limiting creativity and sometimes resulting in considerable frustration [16,17].

Trusty [18-21] & Woolley [22] further disclosed that existing databases on such materials and their formats are not designed to efficiently and directly provide such information to decision makers. They note that the available data on such materials are normally in the read-only format, and are stored in various operational databases that are not easily accessible to decision makers in usable forms and formats. As a result, decision-making failures during the planning and design stage(s) of low-cost green housing projects hinder their use in terms of their industrial capacity utilisation in the housing industry.

While several studies [14,15,20] have emphasized the relative importance of information access in aiding well-considered and justifiable material choices during the early stages of the design process, Wastiels *et al*. [16] argue that the existing material selection method focuses mainly on limited aspects of such materials, in terms of their properties and factors that influence the decision-making process. Quinones [17] asserted that some low-cost green building materials, for example, contain high embodied energy that leads to ecological toxicity and fossil fuel depletion impacts during their manufacturing phase. She argued that ignoring the relevant factors or properties of any of such materials during the crucial material selection phase could reduce the effective life of that product to less than half of its normal effective life span.

Moreover, Seyfang [14] and Trusty [18-22] argue that choosing the right materials for a particular project can be a very complex decision-making task, given that the selection process is influenced and determined by numerous preconditions, decisions and considerations. They suggested the idea of a decision support system (DSS) as a useful aid in making quick and critical decisions during crucial material selection process. They stressed that the considered approach to encourage the wider scale use of low-cost green building materials in mainstream housing should enable design professionals to have easy access to adequate information on the available options, hence, making the selection results more reasonable and bringing more standardization to the material selection decision-making process at the design stage. They went on advising that whatever method is employed must be such that it allows comparison of not only the cost or technical performance of such materials, but also able to take into account several decision-making criteria, so as to derive conclusive and valid evidence of the differing impacts of various material alternatives.

While there seem to be no compelling evidence of technical research on a holistic approach used by design professionals for the evaluation and selection of building materials, previous material assessment models such as the Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Methods (BREEAM), have shown great promise for guiding evaluations of material predictor performance [23]. The findings of the main research study yet, criticised and noted the flawed existing support systems for being partially objective and fraught with problems of fairness [24]. The study revealed that existing methods are found wanting in that they are culturally implicit, and that such methods or tools treat the sustainability [of the] wider built environment as simply a matter of energy and mass flows with little or no regard to the socio-economic, technical, emotive and political dimensions of sustainability [24]. It further revealed that individual country teams establish scoring weights subjectively when evaluating building products, which often pose problems when applied to other regions [25,26]. The analysis of the study however, showed little evidence to justify the assumption that there are tools of demonstrable reliability for designers to assess the sustainability and suitability of such materials or products or their applicability and utility for their potential use in the design of low-cost green housing projects. Hence, a more reliable method is needed to aid design and building professionals in the selection of such building materials and components for low-cost green residential housing projects.

Consequently, to promote more informed decision-making in the selection of low-cost green materials both individually and as assembled building components, a Decision Support System (DSS) is presented in this paper as an aid to design and building professionals. The objective of this study is to support decision-makers in selecting low-cost green building products that are environmentally, socio-culturally, technically and economically balanced through a proposed conceptual system. The model is to facilitate the integration of more sustainable materials into future designs by helping designers quantify how they compare to materials already permitted under existing codes, using the concept of the Analytical Hierarchy Process (AHP). The AHP approach is designed to be practical, as it combines environmental, technical, socio-cultural and economic performance into a single performance value that is easily interpreted.

In the following sections, the reviews of existing technological approaches are summarised and the main findings and themes to emerge from the literature review and the fieldwork seminars and interviews are reported. Then a step-by-step methodology is presented to illustrate the different stages of the DSS model development. Finally, the application of the prototype DSS for selecting appropriate floor material for a residential project in the London Borough of Sutton is demonstrated. The final section concludes the study and suggests areas for further research.

2. Technology in Material Selection: Review

For the past ten years, proven and commercialized technologies have been developed to promote environmental awareness amongst built environment professionals [18,22,23]. Empirical research validates that various studies on building material selection support systems have developed in size and specification within the last ten years [24-26]. Castro-Lacouture *et al.* [26] note that the application of green building support/assessment tools has been widely accepted as an effective and useful way of promoting green housing construction in the housing construction industry. Keysar and Pearce [27] and Bayer *et al.* [28] however, argue that the contexts in which building environmental assessment methods now operate, and the roles that they are increasingly playing, are qualitatively different than earlier expectations. They note that material assessment tools are now classified based on the type of analysis they perform, such as product, assembly, or whole building analysis, or classified as region-specific tools, either considered based on the life-cycle phases they cover, or on the required skills necessary to operate the tool.

While there is clearly an urgent need for new technologies to optimise the use of low-cost green building materials, it is also true that there are many technologies or systems already in use [25-28]. The first real attempt to establish a comprehensive means of simultaneously assessing a broad range of environmental considerations in building materials was the Building Research Establishment Environmental Assessment Method (BREEAM) [28]. The BREEAM tool assesses the environmental impacts of over 150 various materials and components most commonly used in home construction. The tool takes environmental issues into account, then adds measurements and user-defined weighting to arrive at environmental impacts, measured as "Eco-points" for each building material being assessed. Twelve different environmental impacts are individually scored, together with an overall summary rating, which enables users to select materials and components according to overall environmental performance over the life of the building. This scientifically accepted program however, focuses only on the environmental performance of products rather than environmental, social and financial considerations going hand in hand as parts of the material evaluation and selection process.

With emphasis on the Leadership in Energy and Environmental Design tool (LEED), Keysar and Pearce [27] conducted a detailed evaluative study comparing the effectiveness of five different relative importance indices for selecting appropriate material selection tools such as: relative advantage; compatibility; complexity; trialability; and observability, with the goal of improving the sustainability of materials for capital projects. Here, materials such as; regionally manufactured materials, materials with recycled content, rapidly renewable materials, salvaged materials, and sustainably forested wood products are selected based on credit scores. Analyses of their study however, revealed that the LEED model for example specifically requires an energy model, a task often handled by a specialist within a design firm or outsourced to a third party specializing in energy modeling.

Due to the inflexibility inherent in the application of first generation tools, and since they tend to require greater technical expertise to implement, many different tools of the second generation group have also been launched to address these limitations. Among this category is the ATHENA estimator. This has been one of the most popularly used material data-analytic models that analyses over 1200 building material and assembly combinations [28]. It allows the users to look at the life cycle environmental effects of a complete structure or of individual assemblies and to experiment with alternative designs and different material mixes to arrive at the best scenario. Bayer *et al.* [28] noted that the major drawbacks to this tool are the fixed assembly dimensions, software cost, the cost and required skills to use it, the limited options of designing high-performance assemblies, and the overall incomplete assessment of whole buildings environmental impacts [28-30].

With the identified setback associated with ATHENA estimator, The National Institute Standards and Technology (NIST) developed the Building for Environmental and Economic Sustainability (BEES®) 4.0. This model provides a cradle-to-grave product-to-product comparison of over 230 building products based on manufacturer and supply company information [28-30]. The impact categories are weighed, normalized, and merged into a final environmental performance score, to generate a single measure of desirability for product alternatives by combining qualitative and quantitative data. The BEES 4.0 model is however, not capable of providing data for a full LCA of a complete building product, as it only produces data for a limited amount of building materials and evaluative factors [28-31]. These single-attribute claims ignore the possibility that other life-cycle stages or environmental impacts can yield offsetting impacts. Other limitations include; limited product options, limited use for local/regional impact materials and devaluating weighing process [17].

Trusty [18-21] argued that these sets of first and second-generation tools less often consider any of the Multi-Criteria Decision Methods available to solve MCDM problems, adding that some systems do not even consider Life Cycle Cost (LCC) and other performance criteria simultaneously or completely. Moreover, he claimed that the existing performance requirements/criteria approach used in such tools tend to rely on immeasurable characteristics in demonstrating the extent of sustainability in a product, which makes them over-burdensome to implement and communicate.

Since the highlighted material assessment tools were developed primarily to be used in different countries, and the data sources used by each tool differed, further efforts have been undertaken to develop knowledge-based or expert DSS for assistance in material selection. For instance, Rahman *et al.* [32,33] developed an integrated knowledge-based cost model for optimizing the selection of materials and technology for residential housing design using Technique of ranking Preferences by Similarity to the Ideal Solution (TOPSIS). The system is developed to assist architects, design teams, quantity surveyors and self house builders to make decisions for the design from early stage to detailed design stage by ranking the performance and cost criteria of technologies and materials. Loh *et al.* [34] however, criticised the tool for providing partial assistance in the material selection process of the whole building design as it only considers the cost of roofing materials. They argue that material selection process depends on a number of other factors such as the location, zoning and environmental regulations, demographic characteristics, etc. that are not considered in their system. They note that the TOPSIS approach adopted does not only lack the ability to eliminate bias in the selection process but also unable to allow fairer trade-off process.

Loh *et al.* [34] emphasise that strategic selection of sustainable materials and building design prior to the building construction is crucial to increasing building life cycle energy performance. They argue that stakeholders involved in the early design process often have conflicting priorities for both building design and construction materials. They developed an environmentally focused decision support system in the form of an Environmental Assessment Trade-off Tool (EATT), which supports the development of the ideal building design and materials combination that meets stakeholders' requirements. It is designed to assist users select the most appropriate material among a set of candidate materials based on the analytical hierarchy process (AHP) concept of decision-making, since AHP technique has the robust ability to handle the complexities of real world problems, and to deal formally with judgment error, which is distinctive of the AHP method. The system rank orders a set of preselected, technically feasible materials using different decision factors with and without tangible values, such as a clients favour over a particular building design, publicity potential of the building design, life cycle cost, capital cost and energy performance of different materials and building layouts. Zhou *et al.* [12] argued that the approach adopted by Loh *et al.* [34] lacked in robustness as it does not take into account the full-life cycle impacts of newly-accepted building products, and did not specify the sort of materials under studied.

Zhou *et al.* [12] developed a decision support multi-objective optimization model for sustainable material selection. The material selection tools and material data sheets provide extensive information that includes factors such as cost, mechanical properties, process performance and environmental impact throughout the life cycle based on expert knowledge. Wastiels *et al.* [16], confirmed that the tool, however, lack the considerations or descriptions to evaluate the intangible aspects of building materials, which are important to architects. They also criticised the selection methodology for being highly restrictive to a limited range of factors and incompatible with other stakeholders.

Ashby and Johnson (2002) introduce "aesthetic attributes" in the material properties list for product designers when describing material aspects such as the transparency, warmth, or softness. Within the discipline of architecture, however, the intangible qualities of materials are not described and mapped within the current design models. No selection framework was provided to support the implementation of a system.

Wastiels *et al.* [16], proposes a qualitative and quantitative framework to support informed decisions based on physical aspects' and "sensorial aspects" of building materials, but without the tools integration and computerisation as done by Zhou *et al*. [12]. In the presented framework, no pronouncement is made upon how sustainable considerations from these different categories could influence each other, and what MCDM approach could possibly be used if developed.

A similar study by Ding [35], developed a comprehensive assessment decision support system that measures the environmental characteristics of a building product using a common and verifiable set of criteria and targets for building owners and designers to achieve higher environmental standards. Upon analysis it was found that the assessment for her study focused heavily on environmental issues rather than the broader social, cultural, technical and economic aspects of sustainable green construction.

Keysar & Pearce [27] cited extensive research literature describing how material selection tools facilitate the innovation diffusion process and radical decision-making transformation. They however, note that most of the examined models make choices that result in "fabricated assemblies of standardized performance attributes", implying that they do not choose for materials but rather for 'material systems'.

Hopfe *et al*. [36] conducted a study that assessed the features and capabilities of six software tools to screen the limits and opportunities for using BPS tools during early design phases. The tools classification was based on six criteria namely the capabilities, geometric modeling, defaulting, calculation process, limitation and optimization. However, the authors did not report what methodology was used to compile these criteria.

A cost modeling system for roofing material selection was further proposed in Perera and Fernando [37]. Several factors were identified and considered in the selection process. Results demonstrated large inconsistency in the evaluation process. No particular reference was made to the selection methodology.

Other influencing reviews within the scope of this study include Mohamed and Celik [38] who proposed a computerised framework that is responsible for materials selection and cost estimating for residential buildings where users are able to choose their preferred one from list of materials without evaluation and synthesis of multiple design criteria and client requirements. No mention was made about the MCDM technique used for evaluating the list of materials selected and their respective quantities.

Mahmoud *et al*. [39] suggested a method for the selection of finishing materials that covered floors, walls and ceilings and integrates cost analysis at the appropriate decision points, but without the selection information requirements or methodology as proposed in this study.

Lam *et al*. [40] carried out a survey on the usage of performance-based building simulation tools. His study examined the relative impacts and limitations of knowledge-base tools in decision-making. Murray argues that while there is a natural tendency for design and building professionals to focus on the scientific and technological aspects of green and sustainable construction, their approach does not necessarily maximise the positive contributions professionals have to offer if tools are designed to replace professional judgment in the choice of materials. Murray suggests that this is because tools cannot address the intrinsic motivations people need if they are to embrace the positive changes sustainability requires. He continues that limiting the assembly of buildings to the specification of systems would impede the discovery of design opportunities inherent in materials themselves. Similar patterns of consistency, and lack thereof, have also been obtained [for detailed reviews see 17,24-27,31].

By highlighting the different green building material assessment tools, it can be deduced that existing tools are dispersed and based on individual initiatives without a unified consensus based framework [41,42]. It is apparent that each tool has its own unique application. While each tool could be called an LCA tool, there was little consistency in the methodologies used from one tool to another. In addition, while one tool considered the building as a system, other tools considered primarily the product's individual attributes rather than how that specific product performed within the building system [42]. A key question therefore, is whether current assessment methods that were conceived and created to specifically evaluate the environmental merits of conventional building materials can be easily transformed to account for a qualitatively different set of materials.

Giorgetti & Lovell [43] for instance have reported the sub-optimal performance of existing tools. They argued that the subjective values and priorities of the authors of the assessment scheme largely dictate the technical characteristics of the systems, and currently represent the major focus of discussion. They suggest that it is necessary for potential users to analyse the local situation and identify the adaptability of using any tool before applying a universal green building assessment tool to a specific country and region. They warned that some existing tools such as BREEAM, LEED, and even current expert tools might potentially institutionalize a limited definition of environmentally responsible building practice at a time when exploration and innovation should be encouraged in another region.

However, in all the reviewed studies, no efforts to develop a DSS that associates with the corresponding attributes and performance characteristics of low-cost green building materials and components, starting from the broad list of available options in the database to the final selection of the most appropriate material, were found in the existing literature [43,44].

The findings of the review have shown that each of the indices applied in developed regions to deal with issues associated with the impacts and performance of low-cost green building materials in other regions have proven unsatisfactory [44,45]. This finding is premised on the fact that most existing material selection systems have been designed by countries with more developed economies such as the UK, where the scale of social issues and lack of access to resources is simply not as critical as observed in the developing nations [45,46]. The setbacks that associates with the tools reviewed in this research thus, highlights the opportunity for developing a Material Selection Decision Support System (MSDSS), to better address the specific needs and attributes specific to the use of low-cost green materials for tool adopters new to green housing.

The following section briefly highlights the aim and objectives of the study. It extensively describes specific methods adopted for each task in Section 3.1.

3. Research Methodology

In order to identify the key selection factors or variables that formed the basis for the development of the prototype multi-criteria decision support system (DSS), suitable clusters of research approaches were considered in the research exercise, some of which include: exploratory literature reviews, networking with domain experts and practitioners, series of questionnaire surveys and knowledge-mining interviews [47]. **Table 1** provides an overview of the research aim, objectives and the methodology undertaken in four major stages.

3.1. Research Design

To provide a clear theoretical framework for the relatively new area of study, and develop preliminary ideas on issues specific to the research theme within the context of decision-making associated with the impacts of low-cost green building materials and components in housing construction, this study reviewed relevant literature through synthesis and analysis of recently published data, using a range of information collection tools such as; books, and peer-reviewed journals from libraries and internet-based sources. Recognising the limitations of the literature review in terms of examining current research thinking in respect of decision support systems for the selection of low cost green building materials and components, a preliminary research study was undertaken to check and validate prior assumptions in the background and review sections.

In order to build upon knowledge gained from the literature review, and recognising the limitations of the preliminary research survey in terms of examining current research thinking in respect of decision support systems for low cost green building materials and components, a mixed method was adopted for this study. This was followed by in-person interviews to further clarify and elaborate on less detailed and pertinent issues associated with the use low-cost green building materials. The in-depth interviews consisted of 10 participants, who involved a sample of practicing architects, engineers, material specifiers, and a host of building professionals-who influence material choice decisions in the UK housing construction industry. This approach was used to examine the potentials of the proposed MSDSS, (being a tool for the assessment and evaluation of low-cost green materials). It further investigated the effectiveness of design and decision support tools, as well as identified requirements of Life Cycle Assessment (LCA) tools for design decisions at the various stages of the design process.

Consequently, a quantitative questionnaire was developed as the result of the analysis of the results from the interviews. In order to elicit the "most important" factors, a questionnaire survey was conducted among the executives of some selected builder/developer firms. They were asked to rank order from a list of factors (compiled from existing literature on the topic and after initial consultation with some of the executives) based on their judgment and experience. The executives were also asked to indicate desired features they would like to have in a DSS for low-cost green material selection. Since the respondents were widely dispersed, and because it was anticipated that building professionals would be more likely to reply and cooperate with a less time-consuming research method, giving the constraints of time, wider coverage, and budget, it was therefore, decided that a questionnaire sent and returned by email would be the most convenient way of collecting the required data. The inclusion of qualitative open-ended questions provided respondents a chance to express their views more freely.

The target groups of respondents were also taken from a database or directory of building professionals provided by the UK, China, Canada, South Africa, Brazil and US Green Building Councils (GBCs). The selection approach followed the random sampling technique to avoid bias and uneven sample sizes amongst different professional groups, and ensure uniformity, consistency and quality of data. To facilitate the response rate, snowball sampling was also adopted, where the approached respondents were asked to distribute the questionnaire to their colleagues and partners within the field [47].

The selection of South Africa and Brazil for the analysis was due largely to their great similarities in social, economic, and geopolitical terms, and likewise their developed counterparts. In a similar vein, the choice of building experts within the selected countries was as a result of their expertise and advancement in the use and

Table 1. Basic summary of the research methods.

AIM	To develop a decision support system (DSS) that will provide designers with useful and explicit information associated with low-cost green building materials and components, to aid informed decision-making in their choice of materials for low-cost green residential housing projects.		
Stage	Objectives	Tasks	Method
1: REVIEW	1.Examine current views on themes related to decision-making associated with the use of low cost green materials in the housing industry, to identify new ideas & issues arising from the study	**Step 1.** Reviewed relevant literature through synthesis and analysis of recently published data, using a range of information collection tools such as; books, peer-reviewed journals, and articles from libraries and internet base sources	AA,
	2. Review various DSSs currently used at national and international levels for the selection of materials to identify knowledge deficits and the potential benefits associated with their use	**Step 2.** Carried out a preliminary research study with leading researchers who influence the selection of building materials in the field of housing construction	AA, QS, INT
2: DATA COLLECTION &SYNTHESIS	3. Conduct surveys and interviews with building professionals, to identify the potential factors or variables that influence the informed selection of low cost green building materials and components	**Step 3.** Conducted a pilot study, by deploying a test-questionnaire to a small sample of researchers who possess relevant knowledge on issues specific to the use of low cost green materials using the email addresses taken from the databases of recognised building construction companies and research institutions	AA, QS, INT
		Step 4. Conducted the main survey, by administering the revised questionnaire through email contacts taken from databases of interested registered building professional groups, who influence the selection of construction materials from throughout the construction value chain	
		Step 5. Conducted in-person interviews with interested building professionals who influence material choice decision in housing construction using audio recording system to avoid re-contacting the respondents or falsification of information	
		Step 6. Carried out inspection on available expert systems most commonly used in building firms in the UK, USA, China etc. by interviewing experts, with years of experience in the industry, who have implemented or used such systems and directly observing how they function when in operation	
3: DATA ANALYSIS	4. Evaluate and establish the weighted importance of the key factors or variables that will help to determine the relative impacts of the different choices of building materials and components	**Step 7.** Analysed the information and report gathered from the survey exercise(s) using a suite of statistical analytical programs, and various quantitative data analytical techniques	AA, QS M
4: DEVELOPMENT	5. Develop a system to integrate the necessary information appropriate to the informed selection of low-cost green building materials & components	**Step 8.** Assembled the key components by synthesising the relevant databases to be incorporated in developing the proposed DSS model.	AA, QS, M
		Step 9. Developed the main structure workflow of the proposed system by creating links among the various databases,	
	6. Test the functionality of the proposed approach; and validate the effectiveness by applying it to a building material selection problems using a series of case study residential building projects in the UK	**Step 10.** Inputted relevant data to test the internal links to know what needed to be measured within the system, and checking the output of the results against easily calculated values	M
		Step 11. Conducted experts survey by deploying a sample of the prototype system via email of those who participated in the main survey, using feedback questionnaires as a quicker and cost effective means of assessing respondents' judgments about the system	QS
		Step 12. Made necessary changes based on the feedback from the survey	M
		Step 13. Validate the modified prototype system using a series of completed building projects in the UK, by comparing the outputs from the algorithms to monitored data from the completed building	M, CS

KEYS: AA (Archival analysis); INT (Interview); CS (Case study); QS (Questionnaire Survey); M (Modeling).

development of green building tools (as they have had the most uptakes in both geographical regions and being part of an emerging market).

To receive a reasonably sized sample, 500 surveys were sent out by email, over a two-month period of March and April 2012. Using a progressive approach of data collection, a total of 250 respondents returned the completed survey, representing a response rate of 50%. The response rate was accepted as the normal ranges between 20% - 30% were found in most of the construction industry related research [33,34]. Prior to distribution, the questionnaire was pre-tested for comprehensibility by consulting five academics at two universities [47]. A number of changes were suggested and implemented.

Respondents were also invited to post their ideas about current limitations or improvements that should be avoided or integrated in the development of the proposed MSDSS model at the later part of the questionnaire. The questionnaire also examined the adequacy/inadequacy between traditional manual approach of material selection and computer-aided decision support tools. One of the group's participants commented that one of the hallmarks of good science is that a result can be tested independently and proven to be right or wrong in the latter method. The analysis of the questionnaire survey and interviews provided a list of "key" decision-related factors having significant impacts on the process of material selection for residential development as shown in Section 4.1.1.

3.2. Research Findings

The results of the study however, revealed the following.

- Many existing decision support systems in the developed countries do not have the appropriate performance threshold for addressing the most relevant issues specific to less developed countries;
- Current DSS models are unable to relate to matters associated with the informed selection of materials that are commonly used for housing projects in countries with rather less-mature markets;
- The lack of informed knowledge by building professionals in terms of the principles, characteristics, and best practices relevant to the use of low-cost green materials at the design stage, has been identified as a common constraint peculiar to their wider-scale use in the housing industry;
- The majority of building professionals still regard cost and environmental factors as conventional project priorities when selecting building materials or components, but rarely consider the implications of social, political, technical, sensorial, legal and cultural factors in their choice of materials; and finally,
- The majority of low-cost green building materials are yet to be certified under the building regulations, standard specifications and codes of practice; and most importantly,
- There are no demonstrable and compelling evidence of technical research on a holistic approach used by design professionals for the evaluation and selection of low cost green building materials and components at the design stage.

The results of the study thus, provided the platform that suggested the need for a system that could aid informed decision-making to improve understanding, and enhance the effectiveness of actions to implement and promote the wider-scale use of low-cost green building materials and components at the core of the construction business process. In light of their feedback and useful suggestions from building experts who partook in the study, the following portions of the DSS model were either readjusted or improved.

- Easy searchable material selection inputs database;
- Ability to add/remove material selection features with ease;
- Ability to make custom reports;
- Ability to easily navigate all components with ease;
- Comprehensive "HELP or USER INSTRUCTIONS" menu explaining what the tool is doing;
- Being able to understand the material selection process through the lens of non experts;
- Ability to perform trade-off analysis to compare different material options;
- Clarity on the algorithms used to perform the simulations; and Real-time results;
- Data input forms to ensure easy and consistent data input; and,
- Having a huge amount of customizability in terms of output.

After the improvement, the system was shown to the same participants, and minor adjustments were made on the basis of second feedback. In the following sections the proposed MSDSS selection methodology is discussed, and a conceptual framework for the decision support system based on the methodology is presented. Subsequently, the MSDSS model is applied to a hypothetical but realistic material selection problem to rank order the candidate materials for selecting the most appropriate one.

4. System Development

For this research, AHP was selected for its simplicity and due to the fact that it can be easily implemented using any spreadsheet software application such as the MS Excel, as it possesses a powerful macro language that is essential since a menu driven interface had to be developed. Since the intention of the research was not to develop a commercial software product, Macro-in-Excel

VBA (MEVBA) was utilized for the following reasons:

- Macro-in-Excel VBA (MEVBA) has the capabilities to perform all necessary calculations and is common enough that most people are familiar with it;
- It has the ability to write scripts that could automatically convert material data from any graphic table format to an appropriate condensed data table (hidden from the user's view) to allow quick and reliable indexing of material data;
- The Macro-in-Excel VBA framework has the code that makes Windows forms work, so any language can use the built-in code in order to create and use standard Windows forms;
- Makes the application easier to maintain; With MEVBA, codes were easily built into the form or report's definition, since the DSS model contained a large number of macros that respond to events on forms and reports; which would have been difficult to maintain using any other application;
- With Macro-in-Excel VBA it was easy to step through a set of records one record at a time and perform an operation on each record;
- Macro-in-Excel VBA helped to supply a standard security mechanism, which was made available to all parts of the MSDSS data application model;
- Enables the developer to create his own functions: The MSDSS contains a series of mathematical model and computational algorithmic procedures that provided a basis for computing the green development index of material alternatives within an integrated decision-support framework or tool(s).
- Ability to mask error messages during the tests run;
- Enables the system to quickly analyze existing data to discover trends so that predictions and forecasts can be made with reasonable accuracy;
- Allows for extensions and expansions: since the components of the framework are modular, meaning that each may be developed independently, and data may be added as it is acquired to supplement the knowledge and databases, macro-in-excel was used to achieve that goal

4.1. MSDSS Database/Data Warehouse Design

The data warehouse design constitutes the major portion of the MSDSS development and hence will be explained in detail in this section. The data warehouse design essentially consists of four steps as follows:

Step 1: Identifying the key influential factors that will impact on the choice of materials;

Step 2: Designing the material selection methodology framework and identifying the objectives of each step;

Step 3: Designing the various components of the MSDSS model and defining their features and functions;

Step 4: Defining the workflow selection methodology and analytical procedure of the actual prototype MSDSS model

4.2. Identifying the Key Influential Factors

In order to identify the relative importance of the subcategorical factors or variables based on the survey data, ranking analysis was performed. Five important levels were transformed from Relative Index values: Highly Significant Level (H) ($0.8 \le RI \le 1$), High-Medium Level (H–M) ($0.6 \le RI < 0.8$), Medium Level (M) ($0.4 \le RI < 0.6$), Medium-Low Level (M–L) ($0.2 \le RI < 0.4$), and Low Level (L) ($0 \le RI < 0.2$).

From the results of the analysis, 40 factors were identified under the "Highly significant" level for evaluating low-cost green building materials with an RI value ranging from 0.952 to 0.806 and a total of 15 factors, were recorded to have "High-Medium" importance levels with an RI value ranging from 0.795 to 0.652. The analysis of the main survey identified a total of 55 key influential factors out of 60 initial factors as important components of the material selection process.

"Life Expectancy" was ranked as the first priority in the technical category with an RI value of 0.952, and it was also the highest among all factors and was highlighted at "High" importance level. "Resistance to fire" was also rated high in importance among the selection factors. "Maintenance Cost" was ranked third in importance. It was clear from this research that there is a perception of ambiguity surrounding the long-term maintenance of low-cost green building materials. This is not entirely any surprise given that maintenance free buildings are increasingly sought after by clients, anxious to minimise the running costs associated with buildings. "Life-cycle cost" has been, and will continue to be, major concerns for building designers, as well as important traditional performance measure.

Among the top 20 ranking factors, it was observed that only one factor from the environmental category out of the list was ranked high among the selection factors. This again suggests that environmental issues within the context of the developing countries are not strongly considered despite the high environmental awareness exhibited by design and building professionals in developed regions. This finding also corroborates the initial observations of various studies [14,15] repeatedly highlighted in the background and literature studies. They suggest that the problems within the developing regions are characterised by mainly social and economic issues, unlike the developed regions where the scale of social issues and lack of access to basic resources are simply not much of a problem as it is in the developing world.

From **Figure 1**, a total of 15 factors, consisting of 12 site factors, 1 socio-cultural factor, and 2 sensorial factors, were recorded to have "High-Medium" importance levels. Although these 15 variables were in the same importance level category, the "building orientation" factor within the "general/site category" (average RI = 0.652) was considered to be the least important variable compared to the factor "Glossiness" under the "sensorial category" (with an average RI = 0.774), and "material availability" still under the "general/site category" (with an average RI = 0.795). However, it should be noted that site factor accounted for 75% in the "High-Medium" importance level. The result is an example of evidence pointing to the trend that environmental and perhaps site issues are no longer considered as the most important factors for material selection in housing projects, especially within the context of the less developed regions.

Some factors in the three categories were ranked relatively higher in the "High-Medium" level. For example, "material availability (GS1)" was rated as first in the general/site subcategory, and ranked as thirty-fifth in the overall ranking with an RI value of 0.795. An interesting observation from the results is that none of the criteria fell under the medium and other lower importance level. This clearly shows how important the factors are to building designers in evaluating low-cost green building materials. All factors were rated with "High" or "High-Medium" importance levels. However factors such as Compatibility with other materials, Skills availability, and UV resistance fell within the medium-low level. The findings of the analysis asserted that the criteria with medium or low RI does not mean they are not important for selecting materials, but rather created an opportunity to highlight the relative importance of the key criteria from their vantage points. The following shows a framework consisting of the key factors in their order of importance.

4.3. Designing the MSDSS Selection Methodology

The diagram shown in **Figure 2** demonstrates the conceptual framework of the selection methodology for the decision support system. **Table 2** describes a step-by-step procedure of the selection methodology for the material selection decision support system. Section 4.4 presents various components of the MSDSS schema or model.

4.4. Designing the Features of the MSDSS Model

The next stage of the model development was to design the various features of the databases containing the logic and showing relationships between the data organized in different modules. Each module contains the physical information and contents needed to aid in the material evaluation and selection process.

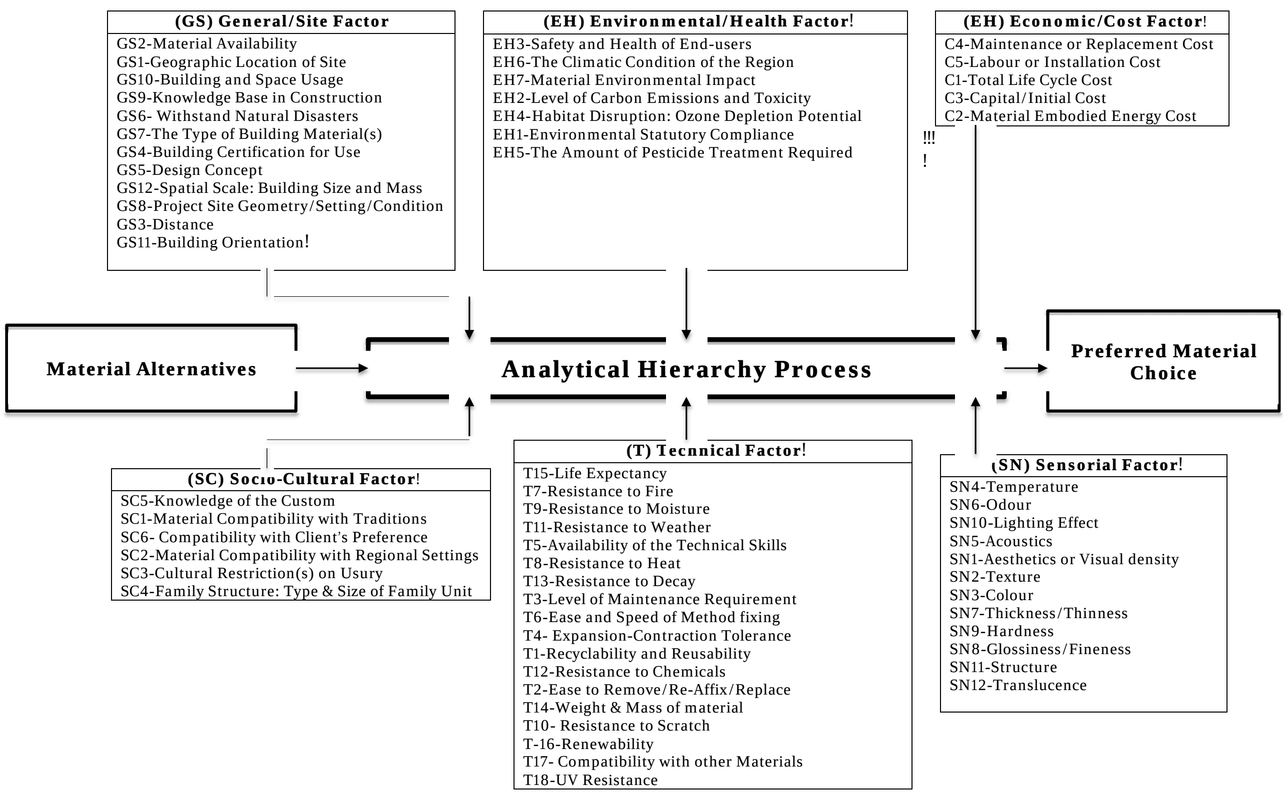


Figure 1. Ranked factors for measuring the impacts of low-cost green building materials.

Table 2. Description of the selection methodoly.

OBJECTIVE	TASK
1. Define or state overall objective/goal	The first step of the methodology is to define the main goal of the intended task.
2. Identify Set of all Possible Material Alternatives to be Assessed	After defining the main goal of the task, the next step is to generate the set of all possible alternatives that are available for selection based on the decision-making parameters. In the material selection process, this comprehensive set of alternatives includes all construction materials and components currently in the database, and the market in context.
3. Prune all infeasible alternatives from set	The third step is to reduce the complete set of alternatives by eliminating/pruning those alternatives, which are clearly infeasible for the intended application from the database consisting of all materials, based on classifications of materials according to the Construction Standards Institute (CSI) Divisions, and material heuristics. For example, if the element under consideration is a structural beam, materials such as roofing sheet and glass are automatically pruned from the set of possible alternatives under consideration, since none of these materials fall under the CSI structural divisions. This should result in a subset of alternatives, all of which would be feasible choices for the intended application. The "pruning" approach is used rather than allowing the user to select feasible materials from the whole set because users tend to overlook alternatives which might be unfamiliar to them but are nonetheless feasible.
4. Evaluate Remaining Alternatives	The fourth step in the methodology is to evaluate the feasible alternatives using the AHP model such that a ranking can be developed according to the relative importance of the material for the intended application.
• Weight Attributes (Decision Factors)	• First, the decision maker weights each factor or variable according to the relative importance that the decision factor or variable holds for the decision maker. It involves the decision-maker replacing probabilities with user weightings for each factor or variable to supplement, not replace, his judgment.
• Calculate Values for Attributes	• Second, values for each of the factors or variables are determined for each material with regard to the manufacturer's information & details of the material or component contained in the material database, and then, a normalized value between zero and one is calculated for each factor value.
• Amalgamate Weighted Attributes	• After weights have been established and values calculated for each attribute against a set of materials or components, the weights and normalized values are multiplied and summed to create an index of preference for that alternative(s).
• Develop Ranking	• Then, a list of alternatives ranked according to the relative importance of the factors or variables is then presented.
5. Review Ranking of Alternatives	When the indices of factors or variables have been calculated for all feasible alternatives, a ranking is developed sorting the alternatives according to each utility value based on the AHP model of decision-making. The alternative with the highest utility value is recommended from the ranked list of potential materials for each design/building element.
6. Select Alternative Based on Ranking	The decision maker may then either elect/decide to select the highest ranked alternative, or choose another alternative from the set based on his professional judgment.
7. Proceed to Next Design Elements	The decision maker satisfied with the selection process, then proceeds to the next design/building element.

The conceptual model/framework of the prototype MSDSS tool consists of a number of interconnected modules/features. A logical model illustrating the developed DSS for material selection is shown in **Figure 3**. **Table 3** describes the functions of each component of the MSDSS model.

4.5. How the System Works

The following steps explain how the prototype MSDSS model works during the material evaluation process.

Step 1: The load manager provides the user with a list of design elements from the "Design Elements" module, and then prompts the user to select the design element of his/her choice in accordance with the terms and specifications of the Construction Standards Institute (CSI) Divisions;

Step 2: The User then selects the particular design element needed for the intended task from a list of design elements (as broken down by the Construction Standard Institute Division);

Step 3: User then enters values for the relevant parameters to answer prompts about areas and dimensions

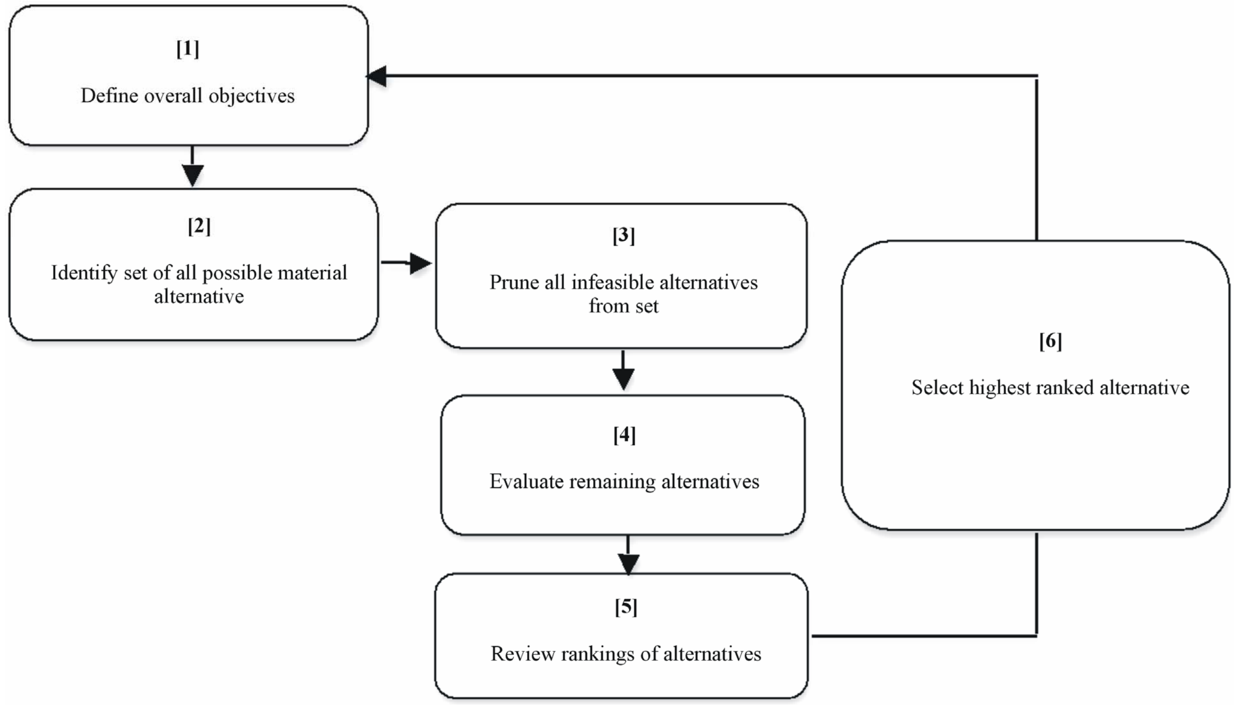


Figure 2. Selection methodology for the MSDSS model.

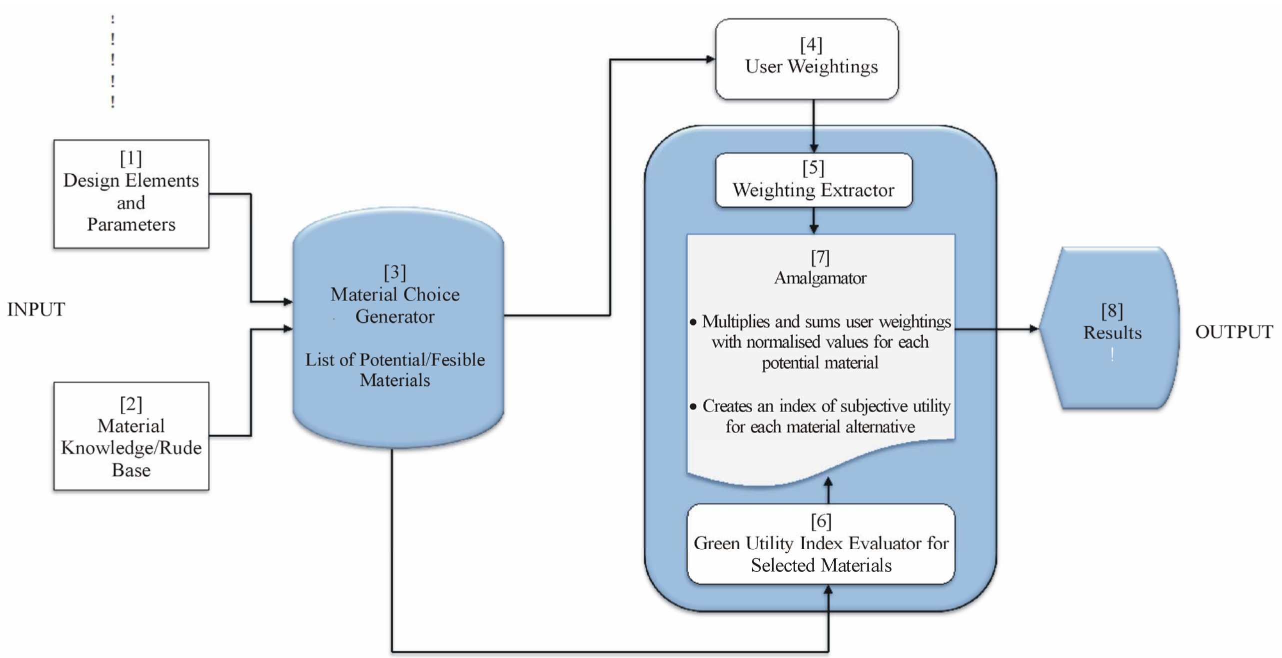


Figure 3. Conceptual framework of the MSDSS model.

of the selected design element, and then sets the threshold values in the material knowledge base

Step 4: The system validates the design parameters and threshold details entered by the user, and then generates the set of all feasible material alternatives that are available for selection, (which includes all categories of construction materials contained in the materials database);

Step 5: After a set of feasible material alternatives has been generated for the "particular design element", the system through the "Weighting Score Extractor Module" prompts the user to obtain weightings for the desired parent and sub-factors according to the relative importance that each factor or variable holds over another based on the decision maker's preference of value;

Step 6: After weights have been established and values calculated for each factor for a particular material, the weights and normalized values are multiplied and summed to create an index of subjective utility for each alternative;

Step 7: The alternative with the highest utility value is recommended by the system;

Step 8: The user reviews the system's recommended choice for each element in the "Result" module, and then either selects the highest ranked alternative, or chooses another alternative from the set based on professional judgment and/or the system's recommendation.

Step 9: The user may choose to generate a printout report or graphical representation of the list of selected materials and green utility indices if desired.

Step 10: The selection process then proceeds to the next design element.

Figure 4 presents a graphical representation of the system workflow.

An illustrative example of the AHP concept is displayed and explained in following section to demonstrate the selection process by applying the prototype MSDSS model to a hypothetical case study design project.

5. Application

The following example illustrates the selection process of floor covering products. It selects the best one among three alternatives. The prototype MSDSS, developed using the AHP technique, was used to select the most appropriate residential building floor material for housing development in the city of London, located in the Sutton County of London. The results demonstrate the capabilities of the MSDSS system in a real-life but hypothetical application scenario. In the following section this process of application is described and discussed.

5.1. A Hypothetical Study Case

The next stage of the model development was to design the various features of the databases containing the logic and showing relationships between the data organized in different modules. Each module contains the physical information and contents needed to aid in the material evaluation and selection process. **Table 4** summarizes the details for the three options of flooring materials for the proposed residential low-cost green housing project. The description of the three options in **Table 4** was based on the standard practices and construction details commonly used in the housing construction industry.

These three (3) floor materials described above will be analysed amongst a host of other material alternatives for the selection of a more sustainable option. In other words, this section will analyse the problem using the MSDSS model, which relies on the use of the AHP mathematical multi-criteria decision-making technique, to identify and decide which material is the most sustainable and suitable flooring material in this case.

To achieve this goal, the MSDSS model was sent to 10

Table 3. Functions of the features of the MSDSS model.

MSDSS Features	Functions
1. Design Elements and Parameters	This feature provides users with a range of building design elements and their respective parameters
2. Material Rule Base	This feature articulates the listing of individual materials in prescribed sequences, gradually eliminating candidate materials based on their inability to meet stated material selection heuristics/rules.
3. Material Choice Generator	This feature contains the material/component database, which generates the set of all possible material alternatives that are available for selection.
4. User's Weightings	Sets preferred weighting value for all attributes to compare with.
5. Weighting Extractor	This feature queries the user to obtain weightings for the factors, based on the user's preference of value on a scale of 1 - 9.
6. Material Index Evaluator	The material index evaluator calculates values of the selected factors or variables for each feasible material choice.
7. Amalgamator	Here the user's weightings are amalgamated (*i.e*. multiplied and summed) with the factor values or weightings for each potential material, resulting in a relative ranking of the feasible materials for each element.
8. Results	- This component provides the ability to view the processed data, and to generate reports. It allows the MSDSS model User Interface to communicate with the user; and also connects all the reports and queries that are generated in the Monitoring databases to the corresponding project files.

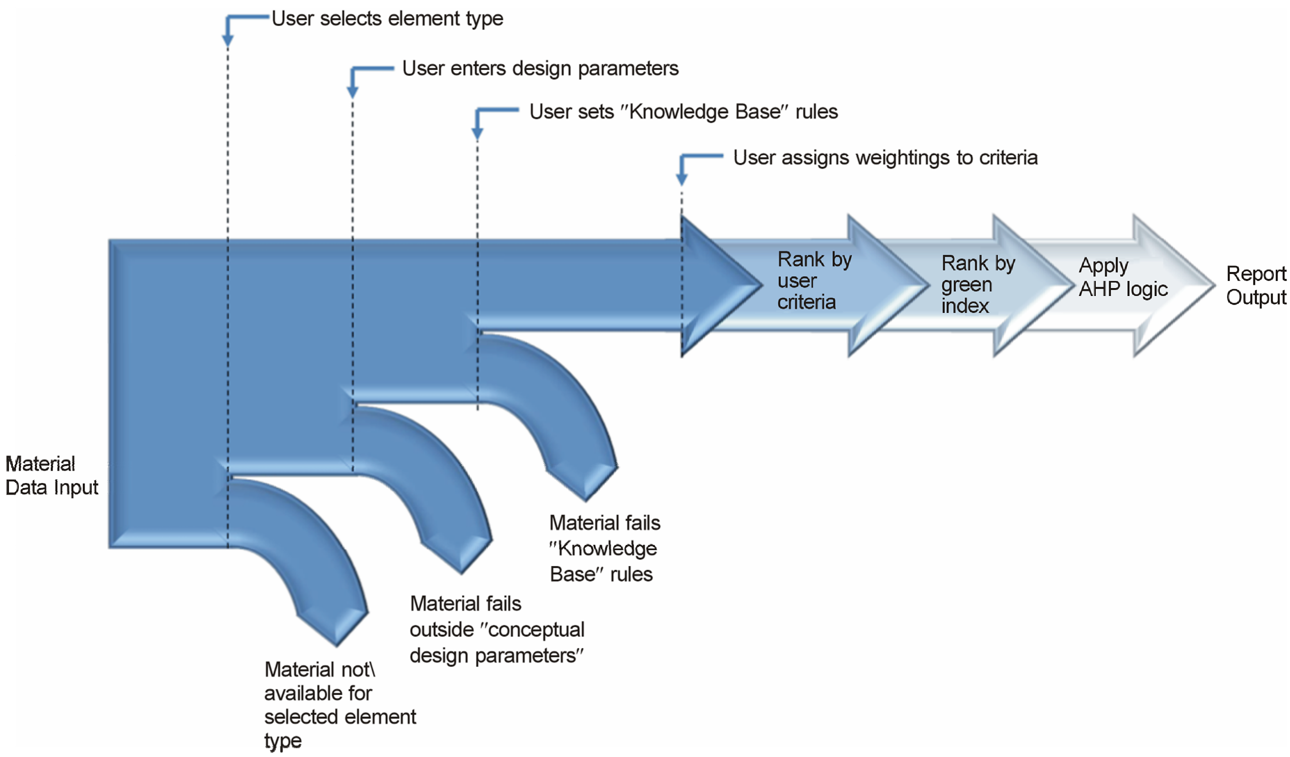


Figure 4. Workflow of the MSDSS model.

Table 4. Summary of the flooring options.

Description	Material A	Material B	Material C
Design Element Type	Paneled Flooring	Laminated Flooring	Concrete Flooring
Building Type	Residential	Residential	Residential
Material Type	Bamboo XL laminated Split Paneled Flooring	Reclaimed/Recycled Laminated Wood Flooring and Paneling	Fly Ash Cement concrete Floor Slab
Size of Materials	230 mm × 150 mm	50 mm × 6000 mm	900 mm × 900 mm

expert evaluators who had the following qualities:

- Considerable amount of knowledge in material analysis based on the AHP concept;
- Used a wide range of green building assessment tools for material selection; and
- Taken part in the previous survey.

The aim of this exercise was to compare their view of the prototype MSDSS model with existing models in terms of their usability, flexibility, and interoperability attributes using the concept of the Analytical Hierarchy Process (AHP).

5.2. Rationale for Adopting the AHP Concept

The study adopted the use of the AHP technique to investigate the interrelationships amongst various criteria and low-cost green material alternatives due to the following reasons:

- AHP is a method that is conceptually easy to use, and decisionally robust to handle the complexities of real world problems;
- It does not require the very strong assumption that the stakeholders make absolutely no errors in providing preference information;
- It has the ability to deal formally with judgment error, which is distinctive of the AHP method;
- The AHP method provides the objective mathematics to process the unavoidably subjective preference inherent in real- world evaluations;
- Possesses an inherent capability to handle qualitative and quantitative criteria important for sustainable material selection; and finally,
- Can enable all members of the evaluation team to visualize the problem systematically in terms of parent criteria and sub-criteria.

Figure 5 shows the flowchart of the material selection computational analysis technique based on the concept of the Analytical Hierarchy Process model. The following sections present details of the evaluation exercise.

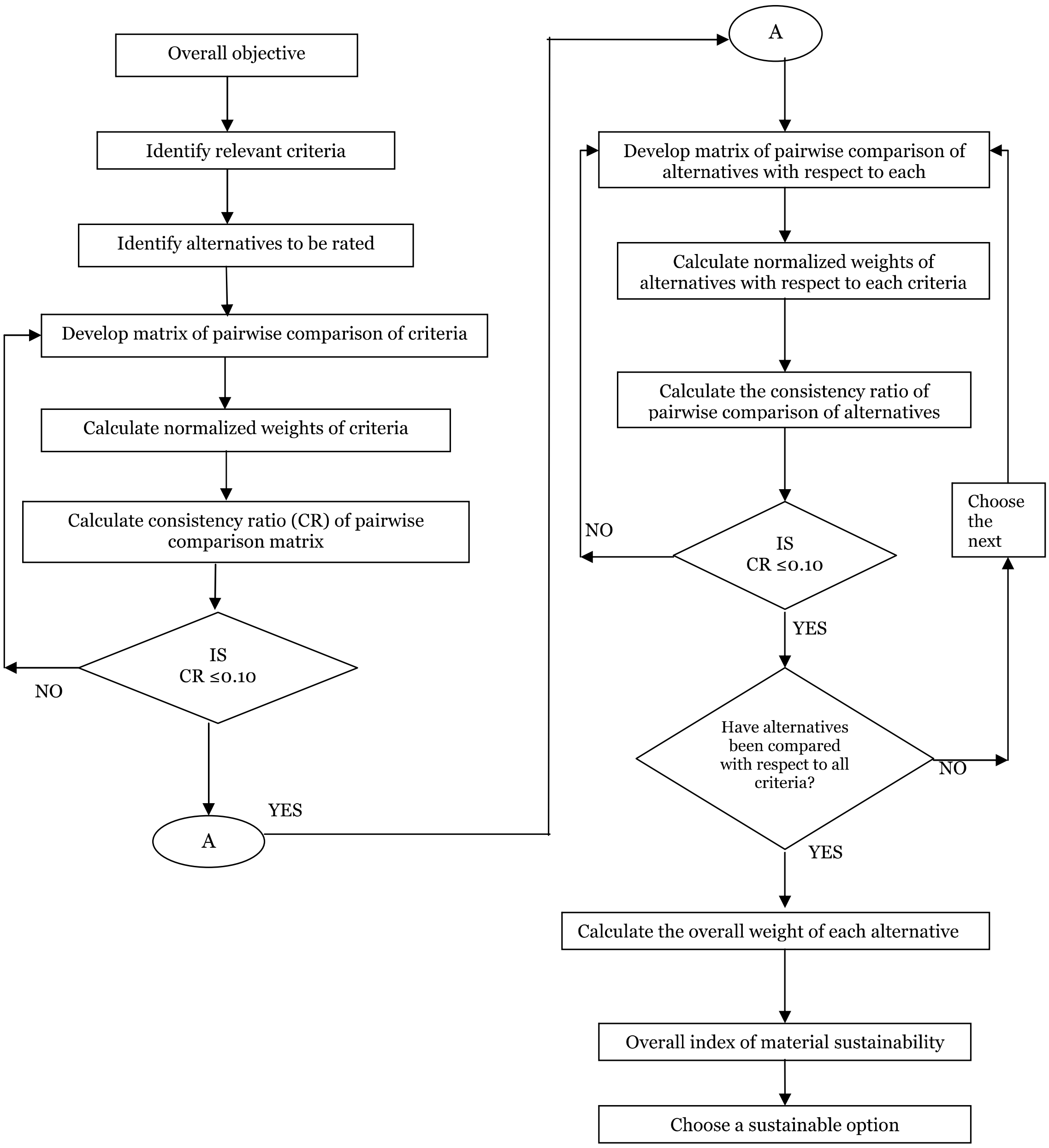


Figure 5. Flowchart of the AHP concept.

5.3. Applying the AHP Model to the Problem

According to Reza *et al*. [48], AHP is a subjective MCDM method that does not necessarily involve or rely on a large sample for its analysis. To better illustrate the procedure of the AHP technique of decision-making, with reference to the case presented in Section 5.1, a complete example of applying AHP to the problem of material selection is provided here based on evaluators' results. Twenty (20) respondents representing various fields of the housing construction industry, and who had fore knowledge of the AHP procedure were selected to participate in the AHP survey.

By evaluating the consistency level of the collected questionnaires, 5 questionnaires out of the 10 received had acceptable consistency and were entered into the system. In order, to avoid arbitrary and inconsistent answers in the data, the mean values of five (5) out of the ten (10) respondents were used to fill out the pair-wise comparison matrices for the parent and sub-factors.

The package included the model, evaluation questionnaire and a cover letter stating the purpose of the research, the validation process and what was expected of them. To conduct the exercise, the study adopted Chua's *et al*. [49] approach based on a number of suggestions as follows:

- A document that reminded and explained the overall aim and objectives of the study to the respondents, followed by a step-by-step demonstration of its operation;
- A demo illustrating a practical exercise. This allowed the evaluators the experience of using the system ensued. During the practical assessment session of the demo, evaluators were able to see the controls and get a general overview of the MSDSS interface;
- An illustrative example of the objective and methodology of the AHP technique based on the instructions in the demo, to guide and illustrate to every respondent on how to browse and conduct analysis;
- After the introduction, a feedback questionnaire was forwarded to the evaluators;
- After each evaluation, each evaluator highlighted their experience(s) and provided feedback on the feel of the system, with special attention to the problems that they encountered during the evaluation process;
- Finally, a reflective or post-user questionnaire was completed to obtain feedback;
- Evaluators were asked to answer each statement or question relating to the model in the questionnaire based on their personal view(s);
- They were also asked to assess the importance of the system based on their perception. Evaluators were also asked to add general comments on the system, and provide feedback on the applicability of the prototype system in assisting in specific material selection problems during their experience and other ways of improvement;
- Problems uncovered or areas that proved difficult to understand during the evaluation process were immediately modified so that it did not arise in subsequent sessions, as this procedure followed each evaluation;
- The respondents were instructed of the relevance of observing consistency in their answers whilst using the MSDSS model;
- The questions relating to different aspects were presented in different sections. This helped respondents to focus on one aspect at a time.

The following sections exemplify the process.

5.4. Decomposition of the Decision Problem

The evaluation exercise provided users with the opportunity to define the problem. **Figure 6** shows the exemplary hierarchy of the problem. The goal is placed at the top of the hierarchy. The hierarchy descends from the more general or parent factors in the second level to sub-factors in the third level to the alternatives at the bottom or fourth level as shown in **Figure 6**). To select a suitable choice among alternatives, the users were instructed to define the decision factors needed for the analysis. In other words, the users determined which alternative could be the best choice to meet the goal considering all the selected decision factors or criteria displayed in **Figure 6**.

The first step of the methodology (as illustrated in figure 2) was to define the main goal of the intended task, by identifying the design element needed for the analysis, and inputting the relevant dimensional scale for the suggested design element (see **Figure 7(a)**).

After defining the main goal of the task, the next step was to generate the set of all possible alternatives that were available for selection with reference to the decision-making parameters as shown in **Figure 7(b)**. At this stage the users are prompted or alerted by the MSDSS model to identify a set of feasible floor material alternatives based on a range of material selection heuristics/knowledge-based rules. The goal is to choose a suitable floor material among options for the project case described in Section 5.1.

5.5. Pair-Wise Comparison of Parent Factors

After selecting the design element, and identifying a set of feasible alternatives using the material selection heuristics/knowledge-based rules, the respondents were made to perform pair-wise comparisons following the demo instruction guide of the MSDSS model. This included the analysis of all the combinations of parent factors and sub-factors relationships. The sub-factors were compared according to their relative importance (based on the ratio scale proposed by Saaty [50-55], with respect to the parent element in the adjacent upper level. After performing all pair-wise comparisons by the decision-makers, the individual judgments were aggregated, basing its analysis on the geometric mean technique as Saaty suggested [52-55].

5.6. Pair-Wise Analysis of the Parent Factors

To avoid arbitrary and inconsistent answers in the data obtained from the 10 participants who consented to partaking in the study, the mean values of five (5) out of the ten (10) respondents were used to fill out the pair-wise comparison matrices for both the parent and sub-factors. The pair-wise comparison matrices obtained from 5 respondents were combined using the geometric mean approach at each hierarchy level to obtain the corresponding consensus pair-wise comparison matrices [54-56]. Using the verbal/ratio scale shown in **Figure 8**, respondents obtained weightings for each parent factor, based on the preference of value(s) on a scale of 1 - 9. The MSDSS model then automatically translated each of the matrixes into the corresponding largest eigenvalue problem and was solved to find the normalised and unique priority weights for each factor (as shown in **Figure 9**). Going by Saaty's [55] rule, the judgment of a respondent

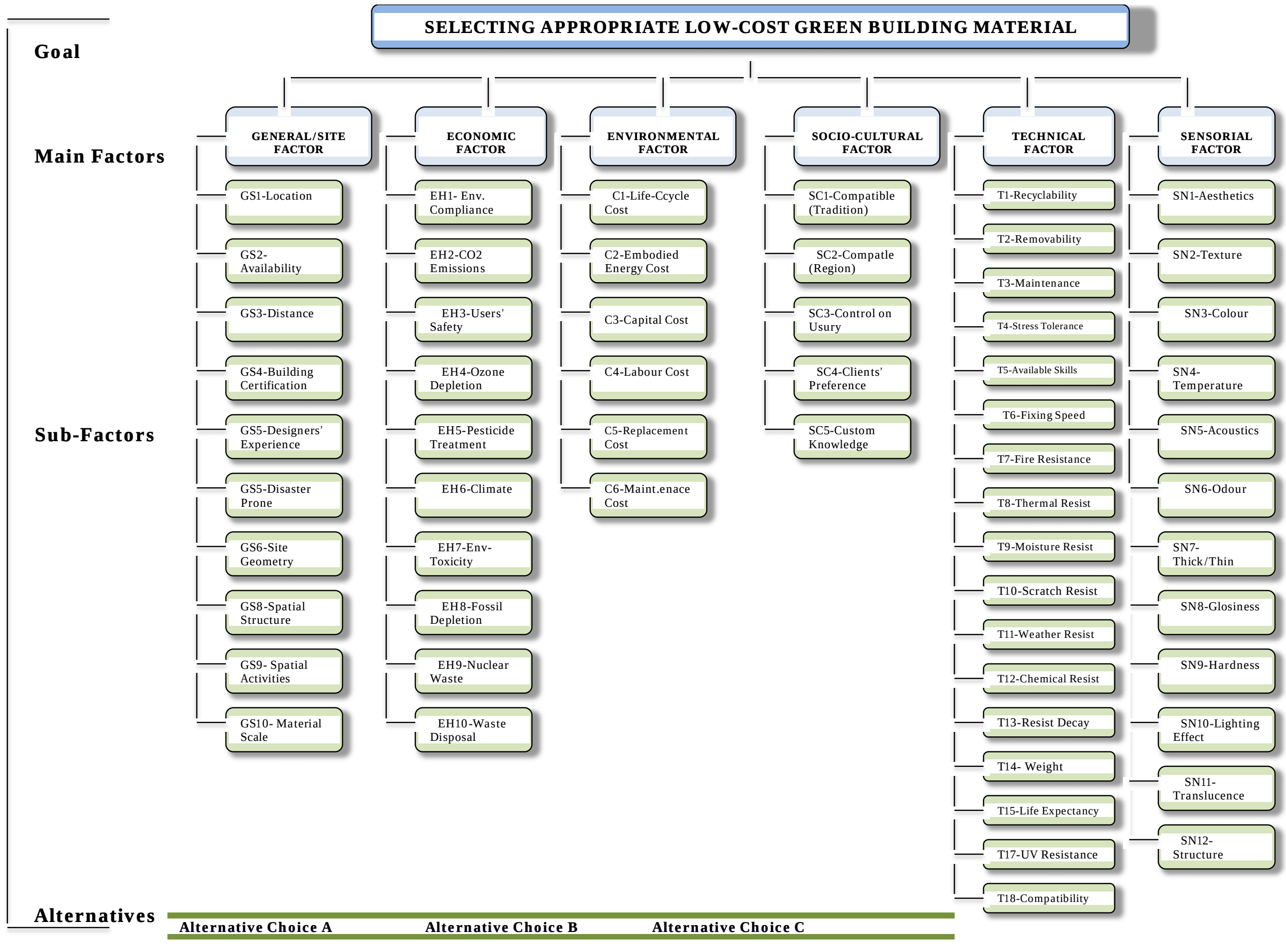


Figure 6. Hierararchy of the material selection phases.

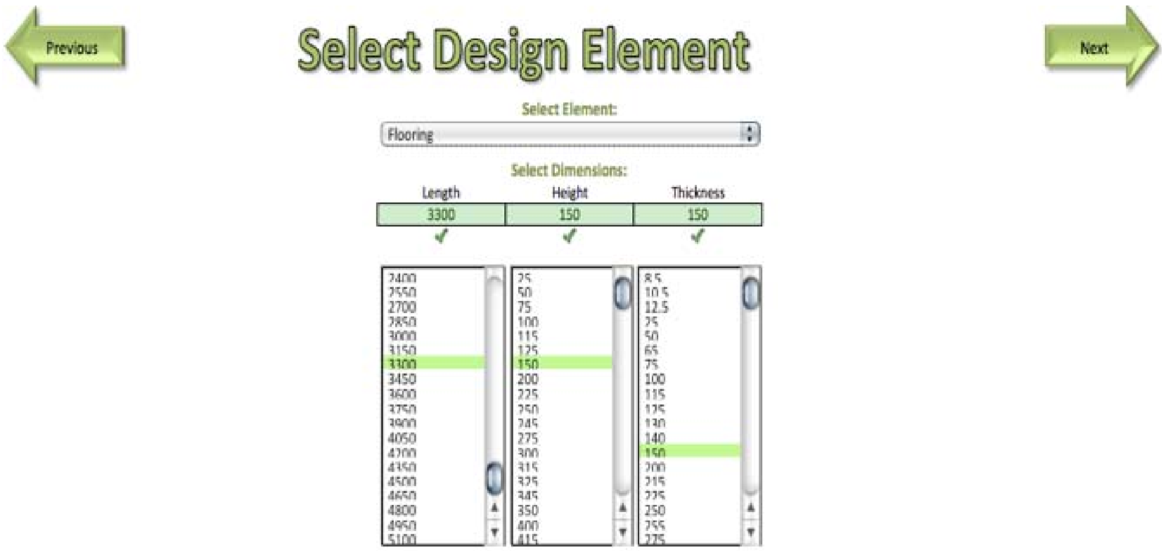
is accepted if the Consistency Ratio (CR) ≤ 0.10. In cases were the results of the respondents were not consistent, the participants were alerted or prompted by the model to carefully re-evaluate the factors until consistency was achieved.

Figures 9 and **10** represent the principal matrix of comparison, which contains the comparison between main/parent factors in relation to the overall objective of the problem (*i.e.*, the selection of a sustainable low-cost green building floor material). From **Figure 9**, it is possible to observe that factor SC is 3 times more important than factor EH. As a logical consequence, factor EH is 3 times less important than factor SC. It is also possible to observe that the elements in the principal diagonal are always equal to 1. In other words, the weight of a criterion in relation to itself, obviously, is always 1.

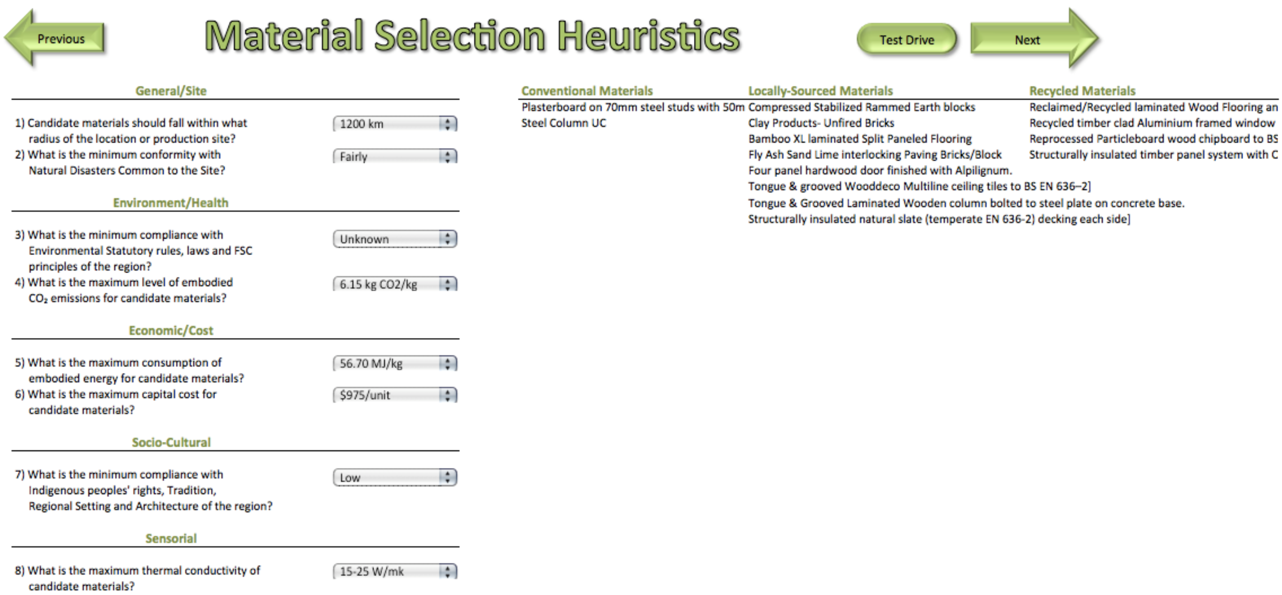
From **Figure 9**, it is also possible to observe that comparing Socio-cultural [SC] and Technical [T] factors, the participants slightly favoured Technical aspects of the products [T], thus arrived at an average value of two (2), derived from the mean calculation of the five respondents. Comparing Socio-cultural [SC] impacts with Sensorial [SN], participants somewhat considered Socio-cultural [SC] as more relevant in their choice of materials than the emotive or sensorial [SN] aspects of the products, thus arriving at a mean score of 2. Comparing Technical [T] and Sensorial [SN], Technical [T] issues where proven to be more relevant or more slightly favoured than others making it the most dominant factor of the three. Based on their preference values, the system automatically creates a reciprocal matrix on the opposite end as the case may be.

At this stage (as shown in **Figure 11**), ratio scales are defined for pair-wise comparison of the main or parent factors using the ratio scale of 1 - 9. As mentioned earlier, the decision makers obtained values for each parent factor based on their aprioristic knowledge and individual weighting preference. Here, the AHP main criteria matrix is then automatically developed by comparing the relative importance of one parent factor over the other as shown above in **Figure 11**.

Next, the parent criteria matrices are normalised (by dividing a cell value by the sum of each column) and then checked for consistency using Eigen values as



(a)



(b)

Figure 7. (a) Dimensional scale for the elected design element; (b) Selection rules for the elected design element.

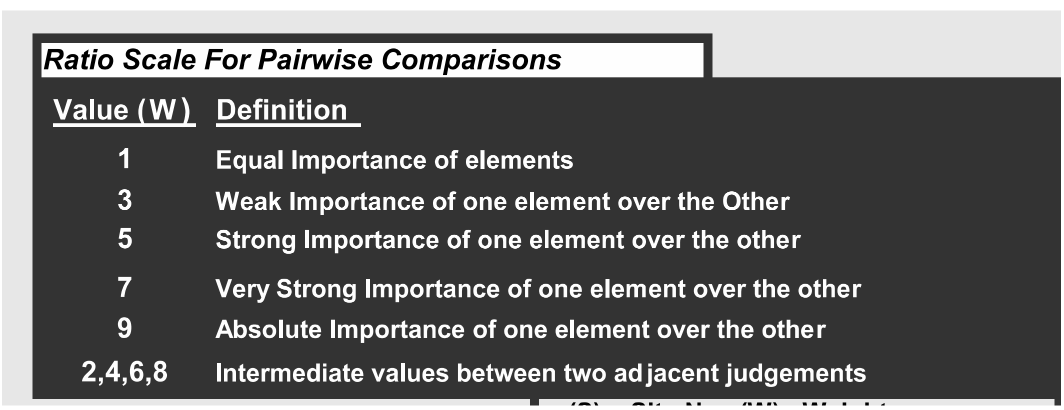


Figure 8. Ratio scale for pair-wise comparison of factors.

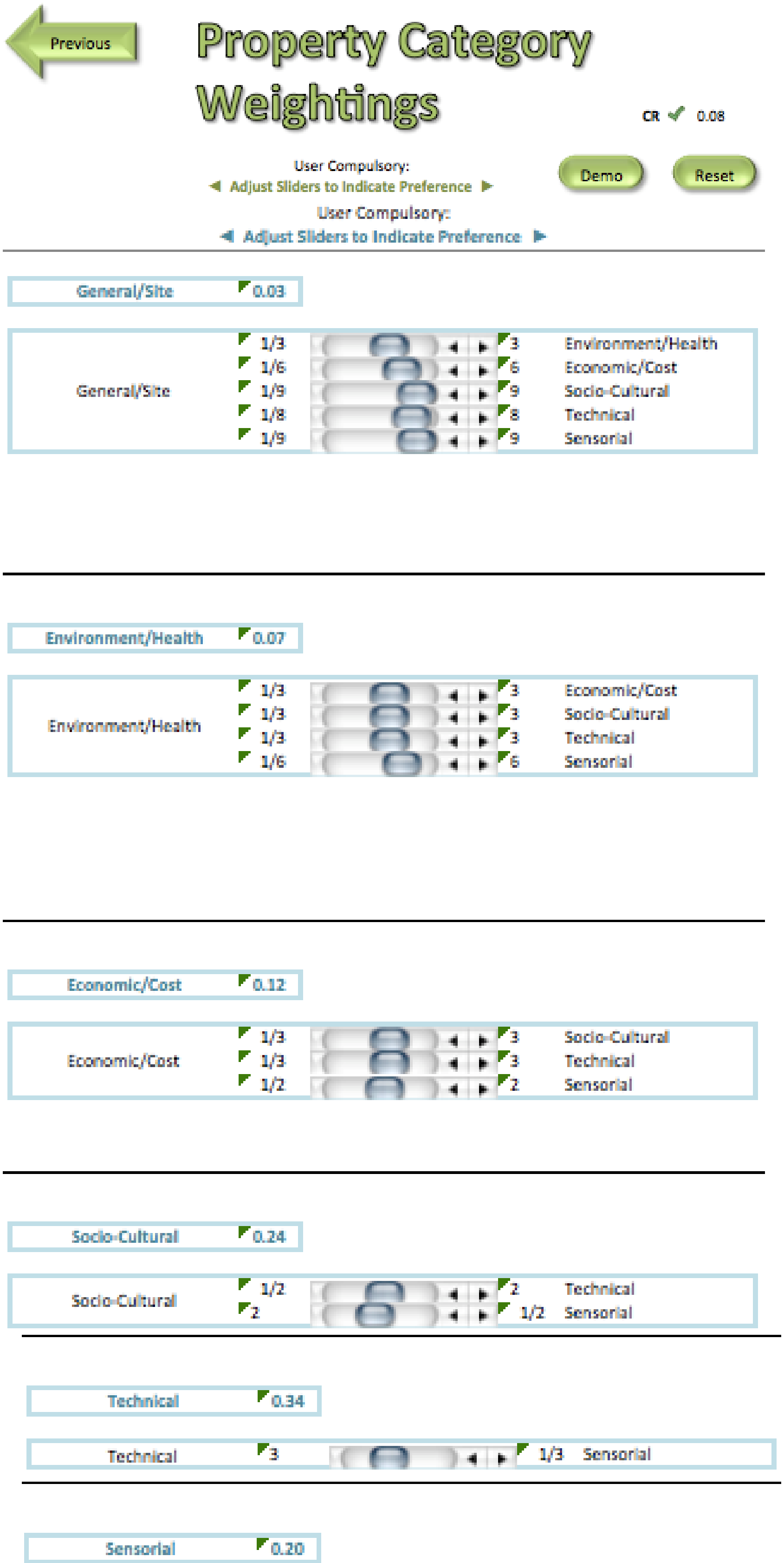


Figure 9. Consensus pair-wise comparison of main factors.

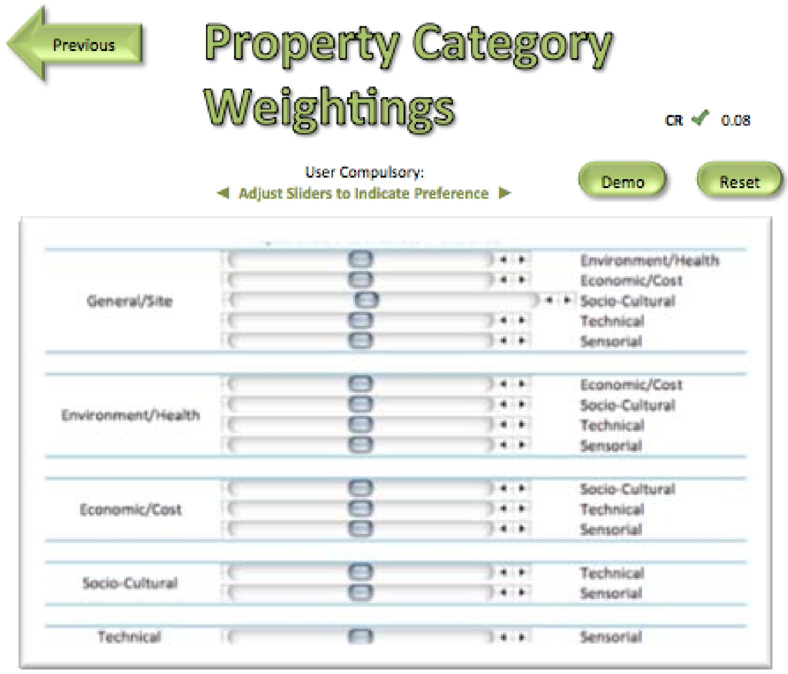


Figure 10. Consensus pair-wise comparison of main factors.

Weighted Criteria Matrix

	General/Site	Environment	Economic/Cost	Socio-Cultural	Technical	Sensorial
General/Site	1.00	0.33	0.17	0.11	0.13	0.11
Environment/Health	3.00	1.00	0.33	0.33	0.33	0.17
Economic/Cost	6.00	3.00	1.00	0.33	0.33	0.50
Socio-Cultural	9.00	3.00	3.00	1.00	0.50	2.00
Technical	8.00	3.00	3.00	2.00	1.00	3.00
Sensorial	9.00	6.00	2.00	0.50	0.33	1.00
Total	36.00	16.33	9.50	4.28	2.63	6.78

Figure 11. Results of pair-wise analysis of parent factors.

shown in **Figure 12**. A local priority vector score is then generated for the matrix of judgments by normalizing the vector in each column of the matrix (*i.e*. dividing each entry of the column by the column total) and then averaging over the rows of the resulting matrix [55]. The normalized eigenvector shown in **Figure 12** represents the relative importance of each parent criteria.

Based on the calculation in **Figure 11**, the relative priorities of the parent factors in the final selection of a sustainable floor material were calculated as displayed in **Figure 12**. The resulting local priority vectors were given as: (GS = 0.030, EH = 0.070, C = 0.120, SC = 0.240, T = 0.340, and SN = 0.200) as shown in **Table 5**.

In order to measure the level of consistency of the matrix for the parent factors, the consistency index (CI) was then calculated at 0.103 (see **Figure 11**). The random index (RI) was also taken into consideration and values calculated at this stage of the evaluation exercise. According to Saaty (2008), for matrix of order 6, the RI is 1.24 (see **Table 6**). Given the two values (consisting of both the consistency index (CI = 0.103) and the relative index (RI= 1.24), the CR was then calculated as:

	Normalised Average Criteria Matrix							
	General/Site	Environment/Health	Economic/Cost	Socio-Cultural	Technical	Sensorial	Av.	λ_{MAX}
General/Site	0.03	0.02	0.02	0.03	0.05	0.02	0.03	0.934297901
Environment/Health	0.08	0.06	0.04	0.08	0.13	0.02	0.07	1.113775203
Economic/Cost	0.17	0.18	0.11	0.08	0.13	0.07	0.12	1.162609985
Socio-Cultural	0.25	0.18	0.32	0.23	0.19	0.30	0.24	1.04719097
Technical	0.22	0.18	0.32	0.47	0.38	0.44	0.34	0.880596922
Sensorial	0.25	0.37	0.21	0.12	0.13	0.15	0.20	1.377336489
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	6.52
							Matrix Size	6
							RI	1.24
							CI	0.103
							CR	0.083064516

Figure 12. Relative priority scores of the parent factors.

Table 5. Derived priority scores of the parent factors.

Factor/Criterion	Relative Priority
General/Site	0.030
Environmental/Health	0.070
Economic/Cost	0.120
Socio Cultural	0.240
Technical	0.340
Sensorial	0.200

Table 6. Random index values for 1 ≤ n ≤ 15.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.55	1.57	1.58

CR = CI/RI = 0.103/1.24 = 0.083 (see **Figure 11**).

According to the AHP model, a matrix is considered as being consistent when the CR is less than 10%. With a Consistency Ratio (CR) of 0.083, the matrix was considered consistent since it was less than 0.1.

5.7. Pair-Wise Analysis of Sub-Factors

The results of the next pair-wise comparison matrices amongst the relative sub-factors are shown from **Figures 13-24**. The same calculations done for the principal matrices of the parent factors were also done for the matrices of the sub-factors. The local priority vector and the consistency ratio for each sub-criterion matrix were also computed and displayed on each corresponding table as fully displayed below.

After comparing each sub-factor according to the user's system of value over other sub-factors, the weightings were obtained to establish each priority weightings in the context of the overall goal: selecting the most sustainable low-cost green floor material. The criteria matrices of each sub-factor were then normalised (by dividing a cell value by the sum of each column) and then checked for consistency as shown in **Figures 13-24**.

5.8. Determining the Weightings of Sub-Factors

The next stage of the assessment process was to find the final weightings of both the parent and sub-factors that will be used subsequently to evaluate the material attributes for sustainable building material selection. To determine the final weightings of the selected factors, the priority vectors (1) of the parent factors are multiplied by the corresponding relative priority vectors of each sub-criterion weighting vectors (2) to obtain the (final) weighting (3) as shown in **Table 7**.

The main/parent factor weighting is derived from users' judgment with respect to a single main criterion. The resultant value of the comparison of each parent factor serves as the priority vector of the main criteria needed for evaluating material attributes. The selected value for

Table 7. Derived final weightings for G-site factors.

Parent factor/Criteria Weighting (1)					Sub-Factor/Criteria Weighting (2)				Final Weighting (3)
Criteria	User Value	Default	CR <0.1	Selected Value	Sub-Criteria	User Value	CR < 0.1	Selected Value	Total = 1.0000
General/Site	0.03	0.057	0.08	**0.026**	**GS1-Location (Mph)**	**0.197**	0.09	**0.197**	**0.0051**
					GS2-Material Availability	0.158		0.158	0.0041
					GS3-Distance to Market (km/h)	0.127		0.127	0.0033
					GS4-Building Certification code	0.115		0.115	0.0030
					GS6-Withstand site natural disaster	0.083		0.083	0.0022
					GS8-Conforms to site geometry	0.114		0.114	0.0030
					GS9-Conforms to spatial structure	0.069		0.069	0.0018
					GS10-Conforms to all spatial activities	0.053		0.053	0.0014
					GS11-Conforms to design geometry	0.044		0.044	0.0012
					GS12-Mat. Spatial scale/Size (sq./m)	0.040		0.040	0.0010

each parent factor as shown in **Table 7** include: GS = 0.026, EH = 0.068, C = 0.122, SC = 0.245, T = 0.335 and SN = 0.203

The sub-factor weighting is derived from user's judgment with respect to each sub-factor. Some of the selected values that serve as the corresponding relative priority vectors of the general/site variable include: 0.197, 0.158, 0.127, 0.115, 0.083, 0.114, 0.069, 0.053, 0.044, and 0.040 as shown in **Table 7**.

Final weighting is derived from multiplying the selected value of the main criteria-weighting or priority vector by the selected value of the sub-factor priority vector. This entry is obtained as follows: $0.026 \times 0.197 = 0.005122$ (as highlighted in **Table 7**). The same process was applied to the other parent factors of the respective categories. The following steps describe the ways by which the various weighting vectors of each criterion are derived.

5.9. Pair-Wise Comparison of the Selected Material Alternatives against Each Sub-Factor

The final step of the exercise was for the respondents to compare each pair of low-cost green material alternatives with respect to each sub-factor. Here the user evaluates the criteria/factors and material alternatives by comparing them through direct rating, to know which factor is more important; how many times; and which material alternative is better in the context of each factor.

The corresponding weightings were based on the importance that the evaluators attached to the dominance of each material alternative relative to all other alternatives under each sub-criterion. These matrices were also normalized and checked for consistency as shown in **Figures 25-38**.

Figures 25-38 present some results of the analyses, which explain the pair-wise matrix priority weightings and normalisation of the various materials with respect to each sub-criterion.

5.10. Determining the Weightings of Sub-Factors

The next phase, after analysing the pair-wise matrices of the sub-factors against the various low-cost green floor material alternatives was to normalize the priority weights for each pair-wise comparison judgment matrices. Once the normalised matrices of the floor material alternatives and various sub-factors were obtained, the values derived from the analysis were multiplied and summed to obtain the final composite priority weights of all material alternatives, focusing particularly on the three floor materials used in the fourth level of the AHP model of decision-making shown in **Figure 6**.

In this case, the final weighting scores (obtained from multiplying the priorities vectors of the parent criteria with that of individual sub-factors), is further multiplied by the priority vector of each material alternative after the pair-wise comparison against each sub-factor (as shown in **Figure 38**). This resulted in a final composite priority/weighting score of each sub-factor for the three floor material alternatives.

	Score	GS1	GS2	GS3	GS4	GS6	GS8	GS9	GS10	GS11	GS12
GS1-Location (Mph)	0.197	1.00	2.00	3.00	2.00	4.00	2.00	2.00	2.00	3.00	3.00
GS2-Material Availability	0.158	0.50	1.00	2.00	2.00	2.00	3.00	3.00	3.00	2.00	3.00
GS3-Distance to Market (km/h)	0.127	0.33	0.50	1.00	2.00	2.00	2.00	3.00	3.00	3.00	2.00
GS4-Building Certification code	0.115	0.50	0.50	0.50	1.00	2.00	2.00	3.00	2.00	4.00	2.00
GS6-Withstand site natural disaster	0.083	0.25	0.50	0.50	0.50	1.00	2.00	2.00	2.00	2.00	2.00
GS8-Conforms to site geometry	0.114	0.50	0.33	0.50	0.50	0.50	1.00	3.00	7.00	3.00	4.00
GS9-Conforms to spatial structure	0.069	0.50	0.33	0.33	0.33	0.50	0.33	1.00	3.00	3.00	2.00
GS10-Conforms to all spatial activities	0.053	0.50	0.33	0.33	0.50	0.50	0.14	0.33	1.00	2.00	2.00
GS11-Conforms to design geometry	0.044	0.33	0.50	0.33	0.25	0.50	0.33	0.33	0.50	1.00	2.00
GS12-Mat. Spatial scale/Size (sq./m)	0.040	0.33	0.33	0.50	0.50	0.50	0.25	0.50	0.50	0.50	1.00
CR	0.09										

Figure 13. Pair-wise matrix for general/site factors.

Normalised Matrix										λ_{MAX}	λ_{MAX}	11
0.210	0.315	0.333	0.208	0.296	0.153	0.110	0.083	0.127	0.130	0.935	**Matrix Size**	10
0.105	0.157	0.222	0.208	0.148	0.229	0.165	0.125	0.085	0.130	0.999	**CI**	0.14
0.070	0.078	0.111	0.208	0.148	0.153	0.165	0.125	0.127	0.086	1.147	**RI**	1.49
0.105	0.078	0.055	0.104	0.148	0.153	0.165	0.083	0.170	0.086	1.103	**CR**	0.09
0.052	0.078	0.055	0.052	0.074	0.153	0.110	0.083	0.085	0.086	1.123		
0.105	0.052	0.055	0.052	0.037	0.076	0.165	0.291	0.127	0.173	1.486		
0.105	0.052	0.037	0.034	0.037	0.025	0.055	0.12	0.127	0.086	1.248		
0.105	0.052	0.037	0.052	0.037	0.010	0.018	0.041	0.085	0.086	1.265		
0.070	0.078	0.037	0.026	0.037	0.025	0.018	0.020	0.042	0.086	1.042		
0.070	0.052	0.055	0.052	0.037	0.019	0.027	0.020	0.021	0.043	0.920		

Figure 14. Normalised matrix for general/site factors.

	Score	EH1	EH2	EH3	EH4	EH5	EH6	EH7	EH8	EH9	EH10
EH1-Env. Statutory Compliance	0.202	1.00	4.00	3.00	2.00	2.00	3.00	3.00	2.00	2.00	2.00
EH2-Embodied CO_2 Emission ($KgCO_2/m^2$)	0.124	0.25	1.00	2.00	3.00	2.00	2.00	2.00	2.00	3.00	0.50
EH3-Human Toxicity-Users Safety level	0.113	0.33	0.50	1.00	2.00	2.00	2.00	3.00	3.00	3.00	0.50
EH4-Ozone depletion rate	0.086	0.50	0.33	0.50	1.00	2.00	2.00	2.00	2.00	2.00	0.33
EH5-Amt. of Pesticide Treatment (l/m^2)	0.078	0.50	0.50	0.50	0.50	1.00	2.00	3.00	2.00	0.33	0.50
EH6-Complies with the Climate of the region	0.067	0.33	0.50	0.50	0.50	0.50	1.00	2.00	2.00	2.00	0.50
EH7-Env. Toxicity (land, water, Animals)	0.053	0.33	0.50	0.33	0.50	0.33	0.50	1.00	2.00	2.00	0.33
EH8-Fossil fuel/Habitat depletion	0.058	0.50	0.50	0.33	0.50	0.50	0.50	0.50	1.00	4.00	0.25
EH9-Nuclear waste rate	0.057	0.50	0.33	0.33	0.50	3.00	0.50	0.50	0.25	1.00	0.33
EH10-Waste Disposal rate	0.162	0.50	2.00	2.00	3.00	2.00	2.00	3.00	4.00	3.00	1.00
CR	0.10										

Figure 15. Pair-wise matrix for environmental factors.

Normalised Matrix										λ_{MAX}	λ_{MAX}	11
0.210	0.393	0.285	0.148	0.130	0.193	0.15	0.098	0.089	0.32	0.960	**Matrix Size**	10
0.052	0.098	0.190	0.222	0.130	0.129	0.1	0.098	0.134	0.08	1.257	**CI**	0.15
0.070	0.049	0.095	0.148	0.130	0.129	0.15	0.148	0.134	0.08	1.191	**RI**	1.49
0.105	0.032	0.047	0.074	0.130	0.129	0.1	0.098	0.089	0.05	1.162	**CR**	0.10
0.105	0.049	0.047	0.037	0.065	0.129	0.15	0.098	0.014	0.08	1.191		
0.070	0.049	0.047	0.037	0.032	0.064	0.1	0.098	0.089	0.08	1.038		
0.070	0.049	0.031	0.037	0.020	0.032	0.05	0.098	0.089	0.05	1.068		
0.105	0.049	0.031	0.037	0.032	0.032	0.025	0.049	0.179	0.04	1.178		
0.105	0.032	0.031	0.037	0.195	0.032	0.025	0.012	0.044	0.05	1.273		
0.105	0.196	0.190	0.222	0.130	0.129	0.15	0.197	0.134	0.16	1.010		

Figure 16. Normalised matrix for environmental factors.

	Score	C1	C2	C3	C4	C5	C6
C1-Total life-cycle cost ($)	0.347	1.00	2.00	2.00	3.00	5.00	9.00
C2-Material embodied energy cost ($)	0.247	0.50	1.00	2.00	4.00	4.00	3.00
C3-Material capital cost ($)	0.186	0.50	0.50	1.00	2.00	4.00	6.00
C4-Labour/Installation cost ($/sqft)	0.120	0.33	0.25	0.50	1.00	3.00	5.00
C5-Material replacement cost ($)	0.063	0.20	0.25	0.25	0.33	1.00	3.00
C6-Material Maintenance cost ($)	0.037	0.11	0.33	0.17	0.20	0.33	1.00
CR	0.07						

Figure 17. Pair-wise matrix for economic/cost factors.

Normalised Matrix						λ_{MAX}	λ_{MAX}	6
0.378	0.461	0.338	0.284	0.288	0.333	0.919	**Matrix Size**	6
0.18	0.230	0.338	0.379	0.230	0.111	1.069	**CI**	0.09
0.18	0.115	0.169	0.189	0.230	0.222	1.101	**RI**	1.24
0.12	0.057	0.084	0.094	0.173	0.185	1.267	**CR**	0.07
0.075	0.057	0.042	0.031	0.057	0.111	1.086		
0.042	0.076	0.028	0.018	0.019	0.037	1.001		

Figure 18. Normalised matrix for economic/cost factors.

	Score	SC1	SC2	SC3	SC4	SC5
SC1-Material compatibility with traditions	0.164	1.00	2.00	0.33	0.50	2.00
SC2-Material compatibility with region	0.102	0.50	1.00	0.50	0.50	0.33
SC3-Cultural restriction on usury	0.362	3.00	2.00	1.00	2.00	3.00
SC4-Client's preference rating	0.227	2.00	2.00	0.50	1.00	2.00
SC5-Conforms to Knowledge of custom	0.146	0.50	3.00	0.33	0.50	1.00
CR	0.08					

Figure 19. Pair-wise matrix for socio-cultural factors.

Normalised Matrix					λ_{MAX}	λ_{MAX}	5
0.142	0.2	0.125	0.111	0.24	1.147	**Matrix Size**	5
0.071	0.1	0.187	0.111	0.04	1.020	**CI**	0.09
0.428	0.2	0.375	0.444	0.36	0.964	**RI**	1.12
0.285	0.2	0.1875	0.222	0.24	1.022	**CR**	0.08
0.071	0.3	0.125	0.111	0.12	1.213		

Figure 20. Normalised matrix for socio-cultural factors.

	Score	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T17
T1-Recyclable	0.09	1.00	2.00	2.00	3.00	0.50	2.00	2.00	0.50	0.50	2.00	3.00	2.00	2.00	2.00	3.00	0.50	0.33	0.50
T2-Ease to remove	0.10	0.50	1.00	0.33	0.33	0.33	3.00	2.00	3.00	0.50	2.00	3.00	2.00	2.00	3.00	2.00	3.00	2.00	2.00
T3- Maintenance level	0.06	0.50	3.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T4-Expansion Tolerance	0.06	0.33	3.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T5-Conforms to skills	0.06	2.00	3.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T6-Ease of fixing	0.05	0.50	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T7-Fire resistance	0.04	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.11	1.00	0.14	1.00	1.00	1.00
T8-Thermal resistance	0.05	2.00	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.14	1.00	1.00
T9-Moisture resistance	0.06	2.00	2.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T10-Scratch resistance	0.05	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T11-Weather resistance	0.05	0.33	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T12-Chemical resistance	0.05	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T13-Resistance to decay	0.07	0.50	0.50	1.00	1.00	1.00	1.00	9.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T14-Weight of material	0.05	0.50	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T15-Life expectancy	0.07	0.33	0.50	1.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.25	1.00	1.00
T16-Biodegradable	0.08	2.00	0.33	1.00	1.00	1.00	1.00	1.00	7.00	1.00	1.00	1.00	1.00	1.00	1.00	4.00	1.00	1.00	1.00
T17-UV Resistance	0.06	3.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T18-Compatibility	0.05	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CR	0.09																		

Figure 21. Pair-wise matrix for technical factors.

Normalised Matrix																		λ_{MAX}	λ_{MAX}	21
0.05	0.11	0.11	0.17	0.02	0.11	0.11	0.02	0.02	0.11	0.17	0.11	0.11	0.11	0.17	0.02	0.01	0.02	1.602	**Size**	18
0.02	0.05	0.01	0.01	0.01	0.17	0.11	0.17	0.02	0.11	0.17	0.11	0.11	0.17	0.11	0.17	0.11	0.11	1.778	**CI**	0.15
0.02	0.17	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	1.083	**RI**	1.69
0.01	0.17	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	1.074	**CR**	0.09
0.11	0.17	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	1.167		
0.02	0.01	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.935		
0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.05	0.01	0.05	0.05	0.05	0.847		
0.11	0.01	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.01	0.05	0.05	0.971		
0.11	0.11	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	1.111		
0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.944		
0.01	0.01	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.926		
0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.944		
0.02	0.02	0.05	0.05	0.05	0.05	0.51	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	1.389		
0.02	0.01	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.935		
0.01	0.02	0.05	0.05	0.05	0.05	0.4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.01	0.05	0.05	1.227		
0.11	0.01	0.05	0.05	0.05	0.05	0.05	0.4	0.05	0.05	0.05	0.05	0.05	0.05	0.22	0.05	0.05	0.05	1.519		
0.17	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	1.083		
0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.972		

Figure 22. Normalised matrix for technical factors.

	Score	SN1	SN2	SN3	SN4	SN5	SN6	SN7	SN8	SN9	SN10	SN11	SN12	SN13
SN1-Aesthetics	0.077	1.00	1	1	1	1	1	1	1	1	1	1	1	1
SN2-Texture	0.077	1.00	1.00	1	1	1	1	1	1	1	1	1	1	1
SN3-Colour	0.077	1.00	1.00	1.00	1	1	1	1	1	1	1	1	1	1
SN4-Temperature	0.077	1.00	1.00	1.00	1.00	1	1	1	1	1	1	1	1	1
SN5-Acoustics	0.106	1.00	1.00	1.00	1.00	1.00	2	0	4	0	2	0	2	2
SN6-Odour	0.087	1.00	1.00	1.00	1.00	0.50	1.00	2	1	0	2	1	2	2
SN7-Thickness/Thinness	0.107	1.00	1.00	1.00	1.00	3.00	0.50	1.00	2	2	2	3	0	0
SN8-Glossiness/fineness	0.075	1.00	1.00	1.00	1.00	0.25	2.00	0.50	1.00	1	1	1	1	1
SN9-Strength/Hardness	0.109	1.00	1.00	1.00	1.00	3.00	5.00	0.50	1.00	1.00	1	1	1	1
SN10-Lighting effect	0.068	1.00	1.00	1.00	1.00	0.50	0.50	0.50	1.00	1.00	1.00	1	1	1
SN11-Translucence	0.108	1.00	1.00	1.00	1.00	6.00	2.00	0.33	1.00	1.00	1.00	1.00	1	1
SN12-Structure	0.089	1.00	1.00	1.00	1.00	0.50	0.50	4.00	1.00	1.00	1.00	1.00	1.00	1
SN13-Thermal	0.083	1.00	1.00	1.00	1.00	0.50	0.50	3.00	1.00	1.00	1.00	1.00	1.00	1.00
CR	0.10													

Figure 23. Pair-wise matrix for sensorial factors.

Normalised Matrix													λ_{MAX}	λ_{MAX}	15
0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	1.000	**Matrix Size**	13
0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	1.000	**CI**	0.15
0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	1.000	**RI**	1.5551
0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	1.000	**CR**	0.10
0.076	0.076	0.076	0.076	0.076	0.153	0.025	0.307	0.025	0.153	0.012	0.153	0.153	1.372		
0.076	0.076	0.076	0.076	0.038	0.076	0.153	0.038	0.015	0.153	0.038	0.153	0.153	1.131		
0.076	0.076	0.076	0.076	0.230	0.038	0.076	0.153	0.153	0.153	0.230	0.019	0.025	1.391		
0.076	0.076	0.076	0.076	0.019	0.153	0.038	0.076	0.076	0.076	0.076	0.076	0.076	0.981		
0.076	0.076	0.076	0.076	0.230	0.384	0.038	0.076	0.076	0.076	0.076	0.076	0.076	1.423		
0.076	0.076	0.076	0.076	0.038	0.038	0.038	0.076	0.076	0.076	0.076	0.076	0.076	0.885		
0.076	0.076	0.076	0.076	0.461	0.153	0.025	0.076	0.076	0.076	0.076	0.076	0.076	1.410		
0.076	0.076	0.076	0.076	0.038	0.038	0.307	0.076	0.076	0.076	0.076	0.076	0.076	1.154		
0.076	0.076	0.076	0.076	0.038	0.038	0.230	0.076	0.076	0.076	0.076	0.076	0.076	1.077		

Figure 24. Normalised matrix for sensorial factors.

Using the priorities determined through these matrices, the weighted overall priority of each candidate material was determined. The amalgamation method yielded a single green utility index of alternative worth, which allowed the material options to be ranked according to their overall priorities. The material with the highest score then becomes the selected candidate material as shown in **Figure 38**. Looking at **Figure 38**, it is clear from the results of the analysis that Material option (A) turns out to be the most preferred material among the three material options identified in **Table 4**, with an overall priority or index score of 0.086. It is based on the concept of the higher the green utility index value, the better the option. The green utility index as calculated for each of the three material alternatives was M(C) = 0.086, M(A) = 0.072 and M(B) = 0.062 for material options C, A and B respectively, making Option C (fly-ash cement concrete floor slab) emerge as the best option amongst the other alternatives as shown in **Figure 38**.

The above example has illustrated the application of the MSDSS in a material selection problem for a proposed 5-bedroom low-cost residential green building project in the London Borough of Sutton. From the illustrated example it can be deduced that the MSDSS model is able to provide rankings in low-cost green building material assessment combining site, economic, technical, social-cultural, sensorial and environmental criteria into a composite index system based on the AHP technique. This model is therefore, based on the presumption that decision makers, given full knowledge of all possible consequences of all possible alternatives and factors, will select the material with the highest-ranking score.

GS1-Location (km)	CSR	CP	RL	B.XL	FA	RT	FPH.	SS	RPB	T&GW	PB	T&G	SC	SIT	
Compressed Stabilized Rammed Earth blocks	1.0	2.0	2.0	4.0	2.0	5.0	8.0	8.0	4.0	4.00	4.0	4.00	7.0	2.00	4.0
Clay Products-Unfired Bricks	0.5	1.0	1.0	3.0	1.0	4.0	7.0	7.0	3.0	3.00	3.0	3.00	6.0	1.00	3.0
Reclaimed/Recycled laminated Wood Flooring and Panelling	0.5	1.0	1.0	3.0	1.0	4.0	7.0	7.0	3.0	3.00	3.0	3.00	6.0	1.00	3.0
Bamboo XL laminated Split Paneled Flooring	0.3	0.3	0.3	1.0	0.3	2.0	5.0	5.0	1.0	1.0	1.0	1.00	4.0	0.33	1.0
Fly Ash Sand Lime interlocking Paving Bricks/Block	0.5	1.0	1.0	3.0	1.0	4.00	7.00	7.00	3.0	3.00	3.0	3.0	6.0	1.0	3.0
Recycled timber clad Aluminium framed window unit	0.2	0.3	0.3	0.5	0.3	1.0	4.00	4.00	0.50	0.50	0.5	0.50	3.0	0.3	0.5
Four panel hardwood door finished with Alpilignum.	0.1	0.1	0.1	0.2	0.1	0.3	1.0	1.0	0.2	0.2	0.2	0.2	0.5	0.1	0.2
Stainless Steel Entry Door.	0.1	0.1	0.1	0.2	0.1	0.3	1.0	1.0	0.2	0.2	0.2	0.2	0.5	0.1	0.20
Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	0.3	0.3	0.3	1.0	0.3	2.0	5.0	5.0	1.0	1.00	1.0	1.00	4.0	0.3	1.00
Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	0.3	0.3	0.3	1.0	0.3	2.0	5.0	5.0	1.0	1.00	1.0	1.00	4.0	0.33	1.00
Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m³ insulation,	0.3	0.3	0.3	1.0	0.3	2.0	5.0	5.0	1.0	1.00	1.0	1.00	4.00	0.33	1.00
Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	0.3	0.3	0.3	1.0	0.3	2.0	5.0	5.0	1.0	1.0	1.0	1.00	4.0	0.33	1.0
Steel Column UC	0.1	0.2	0.2	0.3	0.2	0.33	2.00	2.00	0.3	0.25	0.3	0.3	1.0	0.17	0.3
Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	0.5	1.0	1.0	3.0	1.0	4.0	7.0	7.0	3.0	3.0	3.0	3.0	6.0	1.0	3.0
Structurally insulated natural slate (temperate EN 636-2) decking each side]	0.3	0.3	0.3	1.0	0.3	2.0	5.00	5.00	1.00	1.00	1.0	1.00	4.0	0.3	1.0
Total	5.1	8.7	8.7	23.2	8.7	34.8	74.0	74.0	23.2	23.2	23.2	23.2	60.0	8.7	23.2

Figure 25. Pair-wise matrix: location.

CS	CP	RL	B.XL	FA	RT	FPH.	SS.	RP,	T&G]	PB	T&GW.	SC	SIT	SIS
0.2	0.2	0.2	0.2	0.23	0.14	0.11	0.11	0.17	0.17	0.17	0.17	0.12	0.23	0.17
0.1	0.1	0.1	0.1	0.11	0.11	0.09	0.09	0.13	0.13	0.13	0.13	0.10	0.11	0.13
0.1	0.1	0.1	0.1	0.11	0.11	0.09	0.09	0.13	0.13	0.13	0.13	0.10	0.11	0.13
0.0	0.0	0.0	0.0	0.04	0.1	0.07	0.07	0.04	0.04	0.04	0.04	0.07	0.04	0.04
0.10	0.11	**0.11**	0.13	0.11	0.11	0.09	9.46E-02	0.13	0.13	0.13	0.13	0.10	0.11	0.13
0.0	0.0	0.03	0.02	0.03	0.03	0.05	0.05	0.02	0.02	0.02	0.02	0.05	0.03	0.02
0.0	0.0	0.0	0.0	0.02	0.0	0.01	0.0135134	0.01	0.01	0.01	0.01	0.01	0.02	0.01
0.0	0.0	0.0	0.0	0.02	0.0	0.01	4	0.01	0.01	0.01	0.01	0.01	0.02	0.01
0.0	0.0	0.0	0.0	0.04	0.1	0.07	0.067567568	0.04	0.04	0.04	0.04	0.07	0.04	0.04
0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.067567568	0.04	0.04	0.04	0.04	**0.07**	0.04	0.04
0.05	0.04	0.04	0.0	0.04	0.1	0.1	0.067567568	0.04	0.04	0.04	0.04	0.07	0.04	0.04
0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.067567568	0.04	0.04	0.04	0.04	0.07	0.04	0.04
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.027027027	0.01	0.01	0.01	0.01	0.02	0.02	0.01
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.094594595	0.13	0.13	0.13	0.13	0.10	0.11	0.13
0.0	0.0	0.0	0.0	0.04	0.1	0.07	0.067567568	0.04	0.04	0.04	0.04	0.07	0.04	0.04
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Figure 26. Normalised matrix: location.

EH2-Embodied CO_2 Emission ($KgCO_2/m^2$)	Compressed Stabilized Rammed Earth blocks	Clay Products- Unfired Bricks	Reclaimed/Recycled laminated Wood Flooring and Panelling	Bamboo XL laminated Split Paneled Flooring	Fly Ash Sand Lime interlocking Paving Bricks/Block	Recycled timber clad Aluminium framed window unit	Four panel hardwood door finished with Alpilignum.	Stainless Steel Entry Door.	Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	Steel Column UC	Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	Structurally insulated natural slate (temperate EN 636-2) decking each side]
Compressed Stabilized Rammed Earth blocks	1.0	1.0	5.0	1.0	1.0	5.0	5.0	8.0	2.0	1.0	4.0	5.00	6.00	5.00	1.00
Clay Products—Unfired Bricks	1.0	1.0	5.0	1.0	1.0	5.0	5.0	8.0	2.0	1.0	4.0	5.0	6.0	5.0	1.0
Reclaimed/Recycled laminated Wood Flooring and Panelling	0.2	0.2	1.0	0.2	0.2	1.0	1.0	4.0	0.3	0.2	0.5	1.0	2.0	1.0	0.2
Bamboo XL laminated Split Paneled Flooring	1.0	1.0	5.0	1.0	1.0	5.0	5.0	8.0	2.0	1.0	4.0	5.0	6.0	5.0	1.0
Fly Ash Sand Lime interlocking Paving Bricks/Block	1.0	1.0	5.0	1.0	1.0	5.0	5.0	8.0	2.0	1.0	4.0	5.0	6.0	5.0	1.0
Recycled timber clad Aluminium framed window unit	0.2	0.2	1.0	0.2	0.2	1.0	1.0	4.0	0.3	0.2	0.5	1.0	2.0	1.0	0.2
Four panel hardwood door finished with Alpilignum.	0.2	0.2	1.0	0.2	0.2	1.0	1.0	4.0	0.3	0.2	0.5	1.0	2.0	1.0	0.2
Stainless Steel Entry Door.	0.125	0.125	0.25	0.125	0.125	0.25	0.25	1	0.14	0.125	0.2	0.25	0.3	0.25	0.125
Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	0.5	0.5	4.0	0.5	0.5	4.0	4.0	7.0	1.0	0.5	3.0	4.0	5.0	4.0	0.5
Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	1	1	5	1	1	5	5	8	2	1	4	5	6	5	1
Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	0.25	0.25	2	0.25	0.25	2	2	5	0.3	0.25	1	2	3	2	0.25
Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	0.20	0.20	1.00	0.20	0.20	1.00	1.00	4.00	0.25	0.20	0.50	1.00	2.00	1.00	0.20
Steel Column UC	0.2	0.2	0.5	0.2	0.2	0.5	0.5	3.0	0.2	0.2	0.3	0.5	1.0	0.5	0.2
Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	0.2	0.2	1.0	0.2	0.2	1.0	1.0	4.0	0.3	0.2	0.5	1.0	2.0	1.0	0.2
Structurally insulated natural slate (temperate EN 636-2) decking each side]	1.0	1.0	5.0	1.0	1.0	5.0	5.0	8.0	2.0	1.0	4.0	5.00	6.00	5.00	1.00
Total				8.0	8.0		41.8	8.0	8.0	41.8	41.8	84.0	14.9	8.0	

Figure 27. Pair-wise matrix: embodied CO_2 emissions.

Compressed Stabilized Rammed Earth blocks	Clay Products- Unfired Bricks	Reclaimed/Recycled laminated Wood Flooring and Panelling	Bamboo XL laminated Split Paneled Flooring	Fly Ash Sand Lime interlocking Paving Bricks/Block	Recycled timber clad Aluminium framed window unit	Four panel hardwood door finished with Alpilignum.	Stainless Steel Entry Door.	Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	Steel Column UC	Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	Structurally insulated natural slate (temperate EN 636-2) decking each side]	CI	0.03		
0.12	0.12	0.12	0.1	0.12	0.1	0.1	0.1	0.12	0.12	0.13	0.12	0.11	0.12	0.12	0.12	0.97	RI	1.58
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.12	0.13	0.12	0.11	0.12	0.12	0.12	0.97	CR	0.02
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.05	0.01	0.02	0.02	0.02	0.04	0.02	0.02	0.03	1.07		
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.12	0.12	0.13	0.12	0.11	0.12	0.12	0.12	0.97		
0.1	0.1	0.1	0.1	0.12	0.1	0.12	0.1	0.12	0.12	0.13	0.12	0.11	0.12	0.12	0.12	0.97		
0.0	0.0	0.0	0.0	0.02	0.0	0.02	0.05	0.01	0.02	0.02	0.02	0.04	0.02	0.02	0.03	1.07		
0.0	0.0	0.0	0.0	0.02	0.0	0.02	0.05	0.01	0.02	0.02	0.02	0.04	0.02	0.02	0.03	1.07		
0.015544041	0.015544041	0.005988024	0.01	0.02	0.004	0.01	0.01	0.009	0.015544041	0.03	0.005	0.006	0.005	0.015	0.01	0.88		
0.1	0.1	0.1	0.1	0.06	0.1	0.10	0.1	0.06	0.06	0.10	0.10	0.09	0.10	0.06	0.08	1.18		
0.124352332	0.124352332	0.119760479	0.12	0.12	0.11	0.12	0.1	0.1	0.124352332	0.12	0.11	0.105	0.11	0.122	0.12	0.97		
0.031088083	0.031088083	0.047904192	0.03	0.03	0.04	0.05	0.1	0.021	0.031088083	0.03	0.047	0.057	0.047	0.03	0.04	1.23		
0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.1	0.01	0.024870466	0.01	0.02	0.038	0.02	0.026	0.03	1.07		
0.0	0.0	0.0	0.0	0.02	0.0	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.97		
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.05	0.01	0.02	0.02	0.02	0.04	0.02	0.02	0.03	1.07		
0.12	0.12	0.12	0.1	0.12	0.1	0.1	01	0.1	0.12	0.13	0.12	0.11	0.12	0.12	0.12	0.97		
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	15.5		

Figure 28. Normalised matrix: embodied CO_2 emissions.

C1- Total life-cycle cost ($)	Compressed Stabilized Rammed Earth blocks	Clay Products- Unfired Bricks	Reclaimed/Recycled laminated Wood Flooring and Panelling	Bamboo XL laminated Split Paneled Flooring	Fly Ash Sand Lime interlocking Paving Bricks/Block	Recycled timber clad Aluminium framed window unit	Four panel hardwood door finished with Alpilignum.	Stainless Steel Entry Door.	Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	Steel Column UC	Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	Structurally insulated natural slate (temperate EN 636-2) decking each side]
Compressed Stabilized Rammed Earth blocks	1.0	0.5	3.0	0.5	2.0	7.0	8.0	7.0	7.0	8.0	8.0	8.0	7.0	7.0	7.0
Clay Products- Unfired Bricks	2	1	4	1	3	8	9	8	8	9	9	9	8	8	8
Reclaimed/Recycled laminated Wood Flooring and Panelling	0.3	0.3	1.0	0.3	0.5	5.0	6.0	5.0	5.0	6.0	6.0	6.00	5.00	5.00	5.00
Bamboo XL laminated Split Paneled Flooring	2	1	4	1	3	8	9	8	8	9	9	9	8	8	8
Fly Ash Sand Lime interlocking Paving Bricks/Block	0.5	0.3	2	0.3	1	6	7	6	6	7	7	7	6	6	6
Recycled timber clad Aluminium framed window unit	0.14	0.13	0.20	0.13	0.17	1.00	2.00	1.00	1.00	2.00	2.00	2.00	1.00	1.00	1.00
Four panel hardwood door finished with Alpilignum.	0.1	0.1	0.2	0.1	0.1	0.5	1.0	0.5	0.5	1.0	1.0	1.0	0.5	0.5	0.5
Stainless Steel Entry Door.	0.1	0.1	0.2	0.1	0.2	1.0	2.0	1.0	1.0	2.0	2.0	2.0	1.0	1.0	1.0
Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	0.1	0.1	0.2	0.1	0.2	1.0	2.0	1.0	1.0	2.0	2.0	2.0	1.0	1.0	1.0
Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	0.1	0.1	0.2	0.1	0.1	0.5	1.0	0.5	0.5	1.0	1.0	1.0	0.5	0.5	0.5
Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	0.1	0.1	0.2	0.1	0.1	0.5	1.0	0.5	0.5	1.0	1.0	1.0	0.5	0.5	0.5
Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	0.1	0.1	0.2	0.1	0.1	0.5	1.0	0.5	0.5	1.0	1.0	1.0	0.5	0.5	0.5
Steel Column UC	0.1	0.1	0.2	0.1	0.2	1.0	2.0	1.0	1.0	2.0	2.0	2.0	1.0	1.0	1.0
Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	0.1	0.1	0.2	0.1	0.2	1.0	2.0	1.0	1.0	2.0	2.0	2.0	1.0	1.0	1.0
Structurally insulated natural slate (temperate EN 636-2) decking each side]	0.1	0.1	0.2	0.1	0.2	1.0	2.0	1.0	1.0	2.0	2.0	2.0	1.0	1.0	1.0
Total	7.2	4.3	15.9	4.3	11.1	42.0	55.0	42.0	42.0	55.0	55.0	55.0	42.0	42.0	42.0

Figure 29. Pair-wise matrix: total life-cycle cost.

Compressed Stabilized Rammed Earth blocks	Clay Products- Unfired Bricks	Reclaimed/Recycled laminated Wood Flooring and Panelling	Bamboo XL laminated Split Paneled Flooring	Fly Ash Sand Lime interlocking Paving Bricks/Block	Recycled timber clad Aluminium framed window unit	Four panel hardwood door finished with Alpilignum.	Stainless Steel Entry Door.	Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	Steel Column UC	Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	Structurally insulated natural slate (temperate EN 636-2) decking each side]	Average	Lambda Max	Cl	0.06
0.1	0.1	0.2	0.1	0.18	0.2	0.15	0.17	0.1667	0.15	0.15	0.15	0.17	0.17	0.17	0.15	1.11	RI	1.58
0.2	0.2	0.2	0.2	0.2	0.19	0.1	0.19	0.190	0.163636364	0.163636364	0.163636364	0.19047619	0.19047619	0.19047619	0.20	0.87	CR	0.04
0.05	0.06	0.06	0.1	0.05	0.1	0.1	0.19	0.119	0.11	0.11	0.11	0.12	0.12	0.12	0.09	1.50		
0.2	0.24	0.25	0.2	0.2	0.19	0.16	0.1909	0.190	0.163636364	0.163636364	0.163636364	0.19047619	0.19047619	0.19047619	0.20			
0.0	0.08	0.12	0.07	0.09	0.14	0.12	3	0.14	0.127272727	0.127272727	0.127272727	0.142857143	0.142857143	0.142857143	0.12			
0.02	0.03	0.01	0.03	0.02	0.02	0.04	0.024	0.02	0.04	0.036363636	0.036363636	0.023809524	0.023809524	0.023809524	0.03			
0.0	0.0	0.0	0.0	0.01	0.0	0.02	0.0162	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.02			

Figure 30. Normalised matrix: total life-cycle cost.

SC3- Cultural restriction on usury	Compressed Stabilized Rammed Earth blocks	Clay Products- Unfired Bricks	Reclaimed/Recycled laminated Wood Flooring and Panelling	Bamboo XL laminated Split Paneled Flooring	Fly Ash Sand Lime interlocking Paving Bricks/Block	Recycled timber clad Aluminium framed window unit	Four panel hardwood door finished with Alpilignum.	Stainless Steel Entry Door.	Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	Steel Column UC	Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	Structurally insulated natural slate (temperate EN 636-2) decking each side]
Compressed Stabilized Rammed Earth blocks	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.2	1.0	1.0	0.3	1.0	0.1	1.0	1.0
Clay Products—Unfired Bricks	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.2	1.0	1.0	0.3	1.0	0.1	1.0	1.0
Reclaimed/Recycled laminated Wood Flooring and Panelling	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.2	1.0	1.0	0.3	1.0	0.1	1.0	1.0
Bamboo XL laminated Split Paneled Flooring	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.2	1.0	1.0	0.3	1.0	0.1	1.0	1.0
Fly Ash Sand Lime interlocking Paving Bricks/Block	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.2	1.0	1.0	0.3	1.0	0.1	1.0	1.0

Continued

Recycled timber clad Aluminium framed window unit	3.0	3.0	3.0	3.0	3.0	1.0	1.0	0.3	3.0	3.0	1.0	3.0	0.2	3.0	3.0
Four panel hardwood door finished with Alpilignum.	3.0	3.0	3.0	3.0	3.0	1.0	1.0	0.3	3.0	3.0	1.0	3.0	0.2	3.0	3.0
Stainless Steel Entry Door.	5.0	5.0	5.0	5.0	5.0	3.0	3.0	1.0	5.0	5.0	3.0	5.0	0.3	5.0	5.0
Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.2	1.0	1.0	0.3	1.0	0.1	1.0	1.0
Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.2	1.0	1.0	0.3	1.0	0.1	1.0	1.0
Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	3.0	3.0	3.0	3.0	3.0	1.0	1.0	0.3	3.0	3.0	1.0	3.00	0.20	3.00	3.00
Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.2	1.0	1.0	0.3	1.0	0.1	1.0	1.0
Steel Column UC	7.0	7.0	7.0	7.0	7.0	5.0	5.0	3.0	7.0	7.0	5.0	7.0	1.0	7.0	7.0
Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.2	1.0	1.0	0.3	1.0	0.1	1.0	1.0
Structurally insulated natural slate (temperate EN 636-2) decking each side]	1.0	1.0	1.0	1.0	1.0	0.3	0.3	0.2	1.0	1.0	0.3	1.0	0.1	1.0	1.0
Total	31.0	31.0	31.0	31.0	31.0	14.3	14.3	7.0	31.0	31.0	14.3	31.0	3.4	31.0	31.0

Figure 31. Pair-wise matrix: cultural restriction on usury.

Compressed Stabilized Rammed Earth blocks	Clay Products- Unfired Bricks	Reclaimed/Recycled laminated Wood Flooring and Panelling	Bamboo XL laminated Split Paneled Flooring	Fly Ash Sand Lime interlocking Paving Bricks/Block	Recycled timber clad Aluminium framed window unit	Four panel hardwood door finished with Alpilignum.	Stainless Steel Entry Door.	Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	Steel Column UC	Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	Structurally insulated natural slate (temperate EN 636-2) decking each side]	Average	Lambda Max	CI	0.02
0.0	0.0	0.0	0.0	0.03	0.0	0.02	0.02	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.96	RI	1.58
0.0	0.0	0.0	0.0	0.03	0.0	0.02	0.02	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.96	CR	0.01
0.0	0.0	0.0	0.0	0.03	0.0	0.02	0.02	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.96		
0.0	0.0	0.0	0.0	0.03	0.0	0.02	0.02	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.96		
0.0	0.0	0.0	0.0	0.03	0.0	0.02	0.02	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.96		
0.1	0.1	0.1	0.1	0.10	0.1	0.07	0.04	0.09	0.10	0.07	0.10	0.06	0.10	0.10	0.09	1.23		
0.1	0.1	0.1	0.1	0.10	0.1	0.07	0.04	0.09	0.10	0.07	0.10	0.06	0.10	0.10	0.09	1.23		
0.2	0.2	0.2	0.2	0.16	0.2	0.21	0.14	0.16	0.16	0.21	0.16	0.10	0.16	0.16	0.17	1.16		
0.0	0.0	0.0	0.0	0.03	0.0	0.02	0.02	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.96		
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.02	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.96		
0.10	0.10	0.10	0.1	0.10	0.1	0.1	0.04	0.09	0.10	0.07	0.10	0.06	0.10	0.10	0.09	1.23		
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.028	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.96		

Continued

0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.42	0.22	0.23	0.35	0.23	0.30	0.23	0.23	0.27	0.90
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.02	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.96
0.0	0.0	0.0	0.0	0.03	0.0	0.02	0.02	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.96
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	15.3

Figure 32. Normalised matrix: cultural restriction on usury.

T2-Ease to remove/reaffix/replace	Compressed Stabilized Rammed Earth blocks	Clay Products- Unfired Bricks	Reclaimed/Recycled laminated Wood Flooring and Panelling	Bamboo XL laminated Split Paneled Flooring	Fly Ash Sand Lime interlocking Paving Bricks/Block	Recycled timber clad Aluminium framed window unit	Four panel hardwood door finished with Alpilignum.	Stainless Steel Entry Door.	Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	Steel Column UC	Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	Structurally insulated natural slate (temperate EN 636-2) decking each side]
Compressed Stabilized Rammed Earth blocks	1.0	0.3	0.2	0.2	0.3	0.2	0.2	0.3	0.2	0.2	0.3	0.20	0.33	0.20	0.20
Clay Products—Unfired Bricks	3.0	1.0	0.3	0.3	0.5	0.3	0.3	1.0	0.3	0.3	1.0	0.3	1.0	0.3	0.3
Reclaimed/Recycled laminated Wood Flooring and Panelling	5.0	3.0	1.0	1.0	2.0	1.0	1.0	3.0	1.0	1.0	3.0	1.0	3.0	1.0	1.0
Bamboo XL laminated Split Paneled Flooring	5.0	3.0	1.0	1.0	2.0	1.0	1.0	3.0	1.0	1.0	3.0	1.0	3.0	1.0	1.0
Fly Ash Sand Lime interlocking Paving Bricks/Block	4.0	2.0	0.5	0.5	1.0	0.5	0.5	2.0	0.5	0.5	2.0	0.5	2.0	0.5	0.5
Recycled timber clad Aluminium framed window unit	5.0	3.0	1.0	1.0	2.0	1.0	1.0	3.0	1.0	1.0	3.0	1.0	3.0	1.0	1.0
Four panel hardwood door finished with Alpilignum.	5.0	3.0	1.0	1.0	2.0	1.0	1.0	3.0	1.0	1.0	3.0	1.0	3.0	1.0	1.0
Stainless Steel Entry Door.	3.0	1.0	0.3	0.3	0.5	0.3	0.3	1.0	0.3	0.3	1.0	0.3	1.0	0.3	0.3
Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	5.0	3.0	1.0	1.0	2.0	1.0	1.0	3.0	1.0	1.0	3.0	1.0	3.0	1.0	1.0
Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	5.0	3.0	1.0	1.0	2.0	1.0	1.0	3.0	1.0	1.0	3.0	1.0	3.0	1.0	1.0
Plasterboard on 70 mm steel studs with 50 mm 12.9kg/m^3 insulation,	3.0	1.0	0.3	0.3	0.5	0.3	0.3	1.0	0.3	0.3	1.0	0.3	1.0	0.3	0.3
Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	5.0	3.0	1.0	1.0	2.0	1.0	1.0	3.0	1.0	1.0	3.0	1.0	3.0	1.0	1.0
Steel Column UC	3.0	1.0	0.3	0.3	0.5	0.3	0.3	1.0	0.3	0.3	1.0	0.3	1.0	0.3	0.3
Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	5.0	3.0	1.0	1.0	2.0	1.0	1.0	3.0	1.0	1.0	3.0	1.0	3.0	1.0	1.0
Structurally insulated natural slate (temperate EN 636-2) decking each side]	5.0	3.0	1.0	1.0	2.0	1.0	1.0	3.0	1.0	1.0	3.0	1.00	3.00	1.00	1.00
Total	62.0	33.3	11.0	11.0	21.3	11.0	11.0	33.3	11.0	11.0	33.3	11.0	33.3	11.0	11.0

Figure 33. Pair-wise matrix: ease to remove/affix/replace.

Compressed Stabilized Rammed Earth blocks	Clay Products- Unfired Bricks	Reclaimed/Recycled laminated Wood Flooring and Panelling	Bamboo XL laminated Split Paneled Flooring	Fly Ash Sand Lime interlocking Paving Bricks/Block	Recycled timber clad Aluminium framed window unit	Four panel hardwood door finished with Alpilignum.	Stainless Steel Entry Door.	Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	Steel Column UC	Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	Structurally insulated natural slate (temperate EN 636-2) decking each side]	Average	Lambda Max	CI	0.01
0.02	0.01	0.02	0.0	0.01	0.0	0.0	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.95		RI
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	1.03		CR
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.99		
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.99		
0.1	0.1	0.0	0.0	0.05	0.0	0.05	0.06	0.04	0.05	0.06	0.05	0.06	0.05	0.05	0.05	1.08		
0.1	0.1	0.1	0.1	0.09	0.1	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.99		
0.1	0.1	0.1	0.1	0.09	0.1	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.99		
0.0	0.0	0.0	0.0	0.02	0.0	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	1.03		
0.1	0.1	0.1	0.1	0.09	0.1	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.99		
0.1	0.1	0.1	0.1	0.09	0.1	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.99		
0.0	0.0	0.0	0.0	0.02	0.0	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	1.03		
0.1	0.1	0.1	0.1	0.09	0.1	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.99		
0.0	0.0	0.0	0.0	0.02	0.0	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	1.03		
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.99		
0.08	0.09	0.09	0.1	0.09	0.1	0.1	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.99		
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	15.1		

Figure 34. Normalised matrix: ease to remove/affix/replace.

SN5- Acoustics Performance	Compressed Stabilized Rammed Earth blocks	Clay Products- Unfired Bricks	Reclaimed/Recycled laminated Wood Flooring and Panelling	Bamboo XL laminated Split Paneled Flooring	Fly Ash Sand Lime interlocking Paving Bricks/Block	Recycled timber clad Aluminium framed window unit	Four panel hardwood door finished with Alpilignum.	Stainless Steel Entry Door.	Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	Steel Column UC	Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	Structurally insulated natural slate (temperate EN 636-2) decking each side]
Compressed Stabilized Rammed Earth blocks	1.0	0.2	0.3	0.2	0.2	0.3	0.2	1.0	0.3	0.3	0.3	0.3	0.3	0.3	1.0
Clay Products—Unfired Bricks	5.0	1.0	2.0	1.0	1.0	3.0	1.0	5.0	2.0	2.0	2.0	2.0	2.0	2.0	5.0

Continued

Reclaimed/Recycled laminated Wood Flooring and Panelling	4.0	0.5	1.0	0.5	0.5	2.0	0.5	4.0	1.0	1.0	1.0	1.0	1.0	1.0	4.0
Bamboo XL laminated Split Paneled Flooring	5.0	1.0	2.0	1.0	1.0	3.0	1.0	5.0	2.0	2.0	2.0	2.0	2.0	2.0	5.0
Fly Ash Sand Lime interlocking Paving Bricks/Block	5.0	1.0	2.0	1.0	1.0	3.0	1.0	5.0	2.0	2.0	2.0	2.0	2.0	2.0	5.0
Recycled timber clad Aluminium framed window unit	3.0	0.3	0.5	0.3	0.3	1.0	0.3	3.0	0.5	0.5	0.5	0.5	0.5	0.5	3.0
Four panel hardwood door finished with Alpilignum.	5.0	1.0	2.0	1.0	1.0	3.0	1.0	5.0	2.0	2.0	2.0	2.0	2.0	2.0	5.0
Stainless Steel Entry Door.	1.0	0.2	0.3	0.2	0.2	0.3	0.2	1.0	0.3	0.3	0.3	0.3	0.3	0.3	1.0
Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	4	0.5	1	0.5	0.5	2	0.5	4	1	1	1	1	1	1	4
Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	4.0	0.5	1.0	0.5	0.5	2.0	0.5	4.0	1.0	1.0	1.0	1.0	1.0	1.0	4.0
Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	4	0.5	1	0.5	0.5	2	0.5	4	1	1	1	1	1	1	4
Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	4	0.5	1	0.5	0.5	2	0.5	4	1	1	1	1	1	1	4
Steel Column UC	4.00	0.50	1.00	0.50	0.50	2.00	0.50	4.00	1.00	1.00	1.00	1.00	1.00	1.00	4.00
Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	4.0	0.5	1.0	0.5	0.5	2.0	0.5	4.0	1.0	1.0	1.0	1.0	1.0	1.0	4.0
Structurally insulated natural slate (temperate EN 636-2) decking each side]	1.0	0.2	0.3	0.2	0.2	0.3	0.2	1.0	0.3	0.3	0.3	0.3	0.3	0.3	1.0
Total	54.0	8.4	16.3	8.4	8.4	28.0	8.4	54.0	16.3	16.3	16.3	16.3	16.3	16.3	54.0

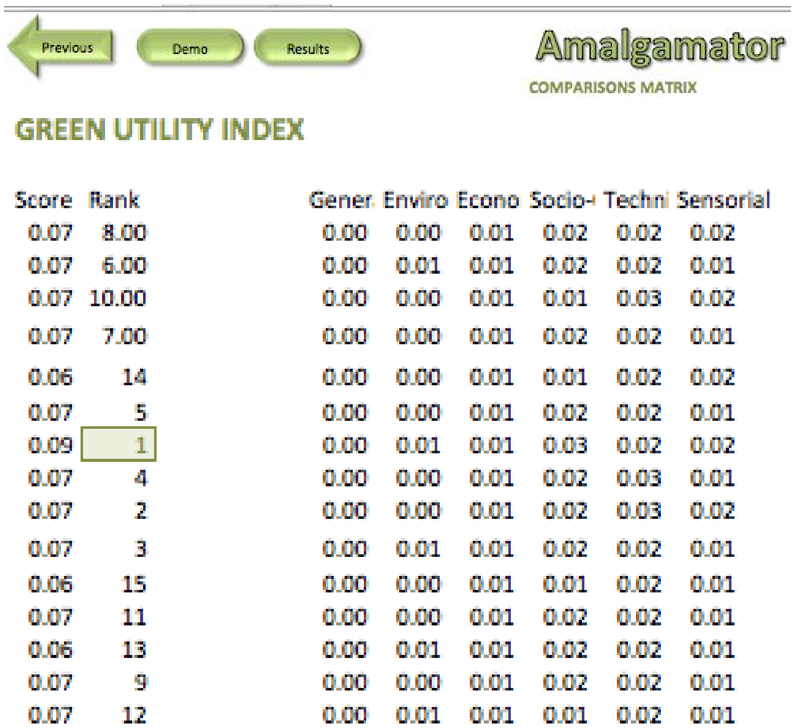
Figure 35. Pair-wise matrix: acoustics performance.

Compress Stabilized Rammed Earth blocks	Clay Products- Unfired Bricks	Reclaimed/Recycled laminated Wood Flooring and Panelling	Bamboo XL laminated Split Paneled Flooring	Fly Ash Sand Lime interlocking Paving Bricks/Block	Recycled timber clad Aluminium framed window unit	Four panel hardwood door finished with Alpilignum.	Stainless Steel Entry Door.	Reprocessed Particleboard wood chipboard to BS EN 312 Type P5,	Tongue & grooved Wooddeco Multiline ceiling tiles to BS EN 636–2]	Plasterboard on 70 mm steel studs with 50 mm 12.9 kg/m^3 insulation,	Tongue & Grooved Laminated Wooden column bolted to steel plate on concrete base.	Steel Column UC	Structurally insulated timber panel system with OSB/3 each side, roofing underlay reclaimed clay tiles	Structurally insulated natural slate (temperate EN 636-2) decking each side]	Average	Lambda Max	CI	0.01
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.97	RI	1.58
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.09	0.12	0.12	0.12	0.12	0.12	0.12	0.09	0.11	0.97	CR	0.01
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.07	0.061	0.06	0.06	0.06	0.06	0.06	0.07	0.06	1.04		
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.09	0.123	0.12	0.12	0.12	0.12	0.12	0.09	0.11	0.97		
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.09	0.123	0.12	0.12	0.12	0.12	0.12	0.09	0.11	0.97		
0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.05	0.030	0.03	0.03	0.03	0.03	0.03	0.06	0.04	1.07		
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.09	0.123	0.12	0.12	0.12	0.12	0.12	0.09	0.11	0.97		
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.018	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.97		

Continued

0.074	0.059	0.06	0.059	0.059	0.071	0.059	0.074	0.061	0.061	0.061	0.061538462	0.62	0.061538462	0.074074074	0.06	1.04
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.074	0.061	0.06	0.06	0.06	0.06	0.06	0.07	0.06	1.04
0.07	0.059	0.06	0.059	0.059	0.071	0.059	0.074	0.061	0.061	0.061	0.061538462	0462	0.061538462	0.074074074	0.06	1.04
0.07	0.059	0.06	0.059	0.059	0.071	0.059	0.074	0.061	0.061	0.061	0.061538462	0.0	0.061538462	0.074074074	0.06	1.04
0.07	0.06	0.06	0.06	0.06	0.07	0.06	0.074	0.06	0.061	0.061	0.061538462	62	0.061538462	0.074074074	0.06	1.04
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.074	0.061	0.06	0.06	0.06	0.06	0.06	0.07	0.06	1.04
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.018518519	0.015384615	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.97
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	15.2

Figure 36. Normalised matrix: acoustics performance.



Score	Rank	Gener	Enviro	Econo	Socio-I	Techni	Sensorial
0.07	8.00	0.00	0.00	0.01	0.02	0.02	0.02
0.07	6.00	0.00	0.01	0.01	0.02	0.02	0.01
0.07	10.00	0.00	0.00	0.01	0.01	0.03	0.02
0.07	7.00	0.00	0.00	0.01	0.02	0.02	0.01
0.06	14	0.00	0.00	0.01	0.01	0.02	0.02
0.07	5	0.00	0.00	0.01	0.02	0.02	0.01
0.09	1	0.00	0.01	0.01	0.03	0.02	0.02
0.07	4	0.00	0.00	0.01	0.02	0.03	0.01
0.07	2	0.00	0.00	0.01	0.02	0.03	0.02
0.07	3	0.00	0.01	0.01	0.02	0.02	0.01
0.06	15	0.00	0.00	0.01	0.01	0.02	0.01
0.07	11	0.00	0.00	0.01	0.02	0.02	0.01
0.06	13	0.00	0.01	0.01	0.02	0.02	0.01
0.07	9	0.00	0.00	0.01	0.02	0.02	0.01
0.07	12	0.00	0.01	0.01	0.01	0.02	0.01

Figure 37. Green utility indices of the selected materials.

6. Potential Benefits of the MSDSS Model

The following are the benefits expected from the application of the MSDSS Model. However the model developed for this research differs from that of the previous works in the following ways:

- The main point of difference from the off-the-shelf assessment tools is that they only trade-off numerical values based on the single-attributes. These single-attribute claims ignore the possibility of what other variables can yield. MSDSS supports trade-off with and without tangible variables, such as a client's preference, environmental statutory compliance, and cultural restriction on usury. This feature is important as decision making in reality engages with solid, verbal and subjective elements.
- In terms of cost, it provides an opportunity for designers to be able to advise their clients as to what the probable financial estimate of the project may be. This helps clients to decide how much they are prepared to spend on different variables of construction.
- A separate set of contextual considerations was included as a heuristics base to facilitate site-specific feasibility and appropriateness testing of each material choice. Boundaries of sustainability inform of knowledge base rules as contained in the MSDSS model could help reduce bias that is often associated with the material selection process.
- Available material assessment tools are particularity ill-adapted for the early stages of the design process and are generally labour intensive. The MSDSS model consists of a resource for relatively small

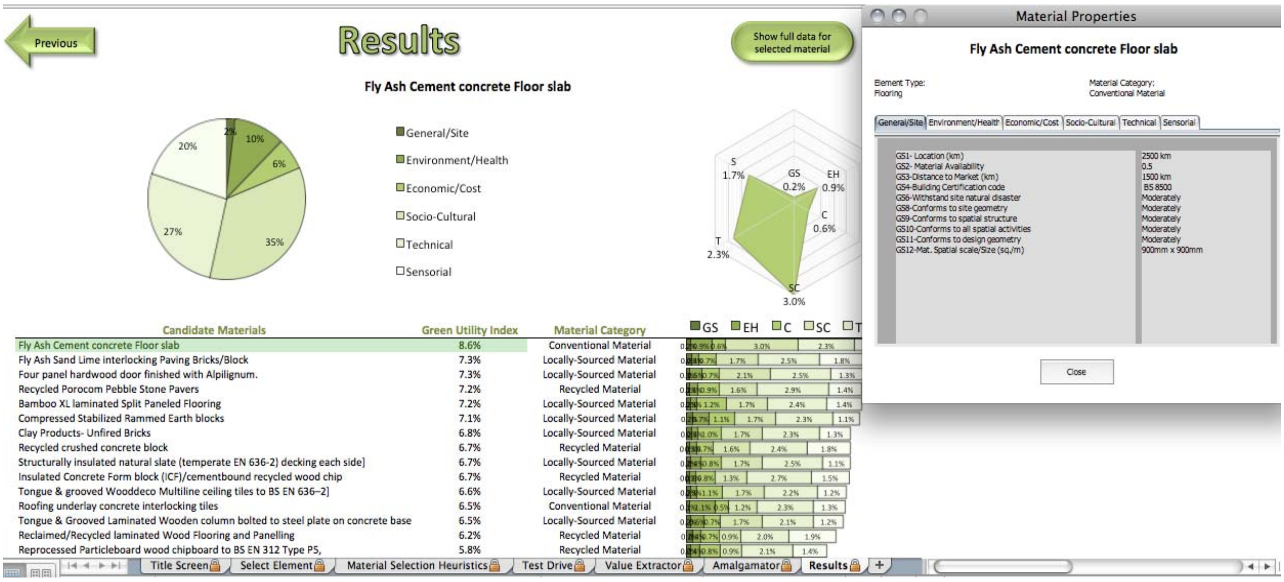


Figure 38. Corresponding indices of the ranked materials.

information input to produce quick and fairly accurate or approximate output of results with little or no training on the part of experienced users. This means that users that may require little training are inexperienced users but not as extensive as obtainable in previous tools.

- There are still significant numbers of smaller firms who cannot afford most material assessment tools because they are extremely expensive. This tool is more or less open source software recommended to provide solution to this challenge.
- Context is a critical consideration for all project decision-making, since even projects located on neighbouring sites will have different end users, and different specific site characteristics. This tool could be applied to other regions with minimal or no changes, and therefore has the ability to adapt to any situation, or change in design according to users' needs or different material alternatives.
- Unlike in the previous models, this tool contains tutorials and help menu as well as video guidance on how to use the software. This provides adequate help to beginners or inexperienced designers.
- For the visual aspect, the MSDSS model has the ability to produce a picture representative of data input rather than abstract. It is able to transfer data from it to other software, applicable to building material selection, and present the properties of each material in a successive window.
- User weightings have been included in the selection methodology to supplement, and not supplant human judgment in the decision-making process. By incorporating user weightings into the selection process, the methodology gains greater acceptability to the user who supplies the weightings.
- Materials change in their innovation, composition, price and availability and most tools find it challenging to update information relating to products. In this MSDSS model, the materials and the corresponding performance of the selected products is updated through a link to the manufacturers web page on the internet, and the users may access more information regarding the selected material or technology through internet from the supplier's web pages.
- The system has been designed to produce an artistic output, accurate, detailed representation and close to reality as much as it can be, without attempt to conceal any feature whether attractive or not;
- Provision of only a limited set of operations or criteria restricts the techniques and solutions that can be applied and consequently restricts the decision-making process. On the other hand, the inclusion of many objectives and the permitting of user specification of input data, system parameters and models, generally increases system flexibility and increases decision support freedom;
- In most tools, AHP technique at the pare-wise comparison stage, tend to be quite cumbersome and often takes a lot of time to maintain the consistency of the response. To eliminate this challenge MSDSS automatically debugs the system at every stage of the evaluation and selection process.
- The system has been thoroughly debugged to be less error prone, so that practitioners can integrate the decisions made by the tools more smoothly into practice, and that it takes less than few seconds to respond to users inputs;
- Responses/feedback from system programmers and

accredited green building experts have also been included in the study to prove the ease of use, applicability and usability of the MSDSS model (see appendix A). As a result, some features have been adjusted based on expert feedbacks to support more reliable and expedient, timelier feedback to different design alternatives or changes.

Reflective Summary

This paper discussed the process of developing a decision-support system to support choices in low-cost green building materials. The research presented in this paper acknowledged the lack of a reliable database model that decision makers can readily use to aid informed decision-making when selecting low-cost green materials for low-cost green residential housing development. The findings from the reviewed literature and the results of the surveyed questionnaire further underscored the need for improving understanding of relevant data associated with the use of such building materials and components, with the goal to change and positively influence the current mental models, attitudes and priorities of multiple stakeholders involved in the production of the built environment, so as to encourage their wider-scale use in mainstream housing.

Based on the data obtained from selected expert builder/developer companies, a prototype MSDSS model was developed to aid designers in making informed decisions regarding their choice of materials for low-cost green residential housing projects. This model was consolidated in to an excel-based decision tool that allows designers to select low-cost green building products from a range of possibilities, and view the resulting impacts and difference in the cost, durability and performance of a range of alternatives. An analysis using the Analytical Hierarchy Process (AHP), based on the results of the participants was performed to show how optimal choices could change with changing user weightings and variables. The participants gained views from participating in the evaluation exercise for a real-life project, including the difficulties in choosing preference scores.

This study thus, indicates that perhaps the development of a DSS model associated with the impacts of low-cost green building materials is useful in that it gives designers a new approach of going through the process of value elicitation, which allows them to explicitly and transparently test the impacts of their elicited values. Providing a visual representation, allowing designers or specifiers to compare multiple alternatives across multiple criteria, was a particularly useful aspect of this study.

7. Conclusions

This report has demonstrated how a DSS model can be used to support multi-stakeholder involvement in the selection of low-cost green construction materials in ways that enable building energy performance and life-cycle cost to be considered at the early stage of residential housing design. The study further reinforced the significance in taking a multi-attribute approach to assessing a building product's sustainable performance. To achieve this goal, the AHP model of decision-making [57-60] was adopted to deal with the ambiguities involved in the assessment of material alternatives and relative importance weightings of multiple factors, given its ability to solve multi-criteria decision-making (MCDM) between finite alternatives.

To prove the validity of the model and the feasibility of the proposed selection methodology, a real-life but hypothetical application scenario was used to further illustrate the application of the MSDSS model in selecting the most appropriate floor material for a single 5-bedroom residential housing project located in the Sutton County of London. The results demonstrated the capabilities of the system, and exposed the way in which the system transparently demonstrates the implications of each step of the analysis. It also proved the practicality of using the MSDSS model, as it combines multiple factors into a single performance value that is easily interpreted.

Since the purpose of this research study was to develop an innovative concept to demonstrate a step-by-step methodology for selecting low-cost green materials with reasonable accuracy and in real time, as opposed to developing a fully-equipped commercial software, macro-in-excel database management technique was used in the back-end of the system to integrate the large volumes of data obtained from multiple sources. Excel was adopted as the database management system since it has the capabilities to perform all necessary calculations and is common enough that most people are familiar with it.

The process followed to develop the prototype MSDSS model in this research demonstrates that, depending on the domain and scope of the problem at hand, a DSS can be built fairly quickly and can be used effectively to help designers quantify how they compare materials that are yet to be certified under the standard specifications and codes of practice, and that which are already permitted under existing codes.

However further work is required to fully validate the MSDSS and the methodology presented. To do so, this research intends to run further case studies ideally using "live" building design projects, by comparing the outputs from the algorithms of the MSDSS system to monitored data from the completed case study building, in order to review the potential savings of the new materials or components proposed by the MSDSS model.

7.1. Contributions to Research and Industry

Insights identified from addressing the research objectives in Section 3 represent part of the original contribution to knowledge made by this study. The following are itemised as key contributions of the study to research and practice:

- The contribution of this research includes the consideration of a holistic approach to low-cost green building product selection based on socio-cultural, technical, emotive, site, cost and environmental performance. Pre-design estimators and pre-construction managers could improve their estimating and product selection practices using the proposed MSDSS tool.
- Material suppliers can also benefit from this approach, as they can use it to enhance their pricing strategies, marketing plans, and overall product competitiveness.
- Decision problems about a product's choice are usually unstructured and ill-defined. By suggesting an alternative means of integrating the available resources associated with the informed selection of low-cost green building materials, it is hoped that the model will help decision makers to further refine their material selection criteria thus, encourage effective decision-making.
- The material selection process is characterized by competitive objectives, involving multiple stakeholders and key actors, dynamic and uncertain procedures and limited timeframes to make significant decisions. The decision makers within this domain: the designers, specifiers and other stakeholders are often confronted with conflicting subjective preferences and fragmented expertise; hence resulting in decision-making failures. The capacity of the system to compare materials using multiple factors with user-specified weightings, will therefore, encourage decision-makers to explicitly consider the effects of their previously-implicit judgments on the outcome of the project, and thus make choices that are timely, and result in more sustainable residential housing project design and implementation.
- The ability to quickly quantify and qualify the suitability outcomes of alternative materials may encourage greater industry acceptance of innovative technology for materials that are yet to be certified under the standard specifications and codes of practice.
- The overall approach used here could be tested in other contexts to determine its generalizability and applicability. In other words, the system could be extended to select materials for commercial development or for any other purpose.
- The material selection factors identified in the prototype model of the MSDSS, provides a unique insight into sustainability and environmental design information requirements for low-cost green housing.
- The adopted research methodology (see **Table 1**) employed to address the research objectives in Section 3 represents part of the original contribution to knowledge made by this study.
- The number of academic publications on the impacts of low-cost green materials was found to be low; hence makes a crucial contribution.
- In the short term, the model could be used in the housing sector as a catalogue of materials to support decision-making in low-cost green housing designs.
- As low-cost green building materials and components become well understood by design and building professionals, there is a likelihood of reducing over-dependency on conventional construction materials in the housing industry.
- The outcome of this study could aid top executives within the housing sector to consider low-cost green materials as part of existing regulatory frameworks and building codes of the Construction Standards Institute (CSI) in capital projects. By doing so, such an approach may create a potential market for local manufacturing and processing of such materials.

7.2. Setbacks, Challenges and Probable Solutions

There were few possible limitations that this research faced during the cause of the study. The limitations are hereby listed for future consideration.

- The process of developing the selection methodology was faced with critical issues that led to several changes in the research methodology and its objectives so many times, in order to achieve the aim of this research.
- Citing prior research studies formed the basis of the literature review and helped lay the foundation for understanding the research problem investigated in this study. However, there were reservations regarding the currency and scope of the research topic, as there was no compelling evidence of prior research on the topic. As literature on DSS for low-cost green housing design is still relatively low, the study therefore had to rely on the most current reports, interviews, and observations from the different and various organisations, and building professionals for its information.
- It remains true that sample sizes that are too small cannot adequately support claims of having achieved valid conclusions and sample sizes that are too large do not permit the deep, naturalistic, and inductive analysis that defines qualitative inquiry [47]. Yin [47] noted that determining adequate sample size in qualitative research is ultimately a matter of judgment and experience in evaluating the quality. Hair *et al.* [61] warned that it is important to consider not only the

statistical significance, but also the quality and practical significance of the results for managerial applications, when analysing data. They noted that unequal or uneven sample sizes amongst different professional groups could also bias or influence the results as getting equal sample sizes from different groups of respondents was unrealistic and demanding. To address this issue the study adopted a sampling strategy using the stratified random sampling approach where each group of the sample population had reasonable number of randomly selected participants, which helped to achieve sampling equivalence between the researcher and professionals of the various building professions both in higher institutions and practicing building design and housing construction firms.

- Giving that most respondents were practicing professionals, getting a list of the sample population for the study was very discouraging. Having access to people, and organizations, was otherwise limited, giving the time differences and tight-scheduled activities. However the use of progressive approach of reminding the subjects using any available means either through e-mails, LinkedIn, Facebook, Twitter or through phone calls helped to address this problem.
- Very few of the participants had little exposure to AHP quantitative-based decision-making process. Though they found the process a bit daunting, they were somewhat comfortable with the idea of ranking preferences, as they were used to considering the choice for alternatives based on unquantified methods, but without assigning personal values to criteria. Prior help manual sent to participants before embarking on expert evaluation survey helped to reduce the complexities associated with the MCDM technique adopted.

7.3. Potential Areas for Further Studies

Several areas were identified as potential areas for further research as itemised below:

- Although not demonstrated in this system but it is also possible that potential researchers can redesign or customize the database to best fit the needs of any particular region or could be extended to select materials for commercial development;
- While the findings of this research focused specifically on a subset of design and building professionals involved with public residential housing sector projects, the overall approach used here could be tested in other contexts to determine its generalizability and applicability.

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APPENDIX A: Feedbacks from Evaluators

The following are feedbacks and suggestions retrieved from users on the MSDS tool. The names of the participants were undisclosed to respect their anonymity.

"The system relates to issues concerned with local knowledge, local materials data, local climate know-how, local experts needed to operate system, which are hardly considered in other systems". I think it shows great promise and the mechanics are very well-developed and user-friendly,

"Material costs vary from location to location (especially in the USA where material costs vary not just from state to state but also from city to city". Perhaps when the material selection is sorted by the element choice, this will seem more useful".

"It depends on what resources you are referring to; if referring to the underlying database, those are considerable. If referring to the resource needs of the organization that would use the model, not too costly to operate".

"The interface is very well-designed and easy to navigate. However, there is a need for more explanatory material to allow the user to understand what s/he is actually doing, and how to operate some parts of the model appropriately".

"In terms of its operation, interoperability, flexibility, usability and applicability, per se, it is very clear and straightforward; it's the underlying premise and data that needs little clarification in order for the user to operate the model effectively.

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Architectural Features of Stilted Buildings of the Tujia People: A Case Study of Ancient Buildings in the Peng Family Village in Western Hubei Province, China

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ABSTRACT

This paper describes and analyzes the stilted buildings of the Tujia people (an ethnic group living in mainland China), a distinctive building style unique to them, from the perspectives of site selection, spatial layout, construction techniques, and cultural inheritance. The cluster of stilted buildings (*Diaojiao Lou* in Mandarin Pinyin) in the Pengjia Village (meaning most of the villagers share the surname of Peng) is presented as a case study in this paper. The paper makes a case for their preservation as authentic carriers of the Tujia people's cultural history, which is quickly disappearing due to development pressures. Three preservation strategies are discussed to meet this preservation goal. The first is to provide a detail analysis of the construction language to guarantee authenticity in the documentation, preservation and restoration processes of the stilted buildings. The second is to keep alive the expert knowledge and skill of traditional artisans by involving them in the construction of new structures using *diaojiaolou* techniques. The third strategy is to encourage local people to "dress-up" discordant buildings constructed mid to late 20th century with well-mannered facades using traditional details such as suspension columns, *shuaqi*, and six-panel and bang doors. Taking as a whole, these strategies are presented to help local residents, preservation experts, developers and policy makers sustain the irreplaceable cultural heritage and economic independence of the Tujia people.

Keywords: Tujia People; Stilted Buildings; Ancient Architecture Surveying; Traditional Structural Features; Traditional Spatial Features

1. Introduction

Stilted buildings are unique to the Tujia people living in the mountainous region of western China, including Hubei Province, Chongqing municipality, Hunan Province, and Guizhou Province. They are typical architectural structures carefully adapted to the local ecology, environment, and geography, characterized by steep mountains and wood-covered topography, a moist and rainy climate, extremely hot summers, and severe winters [1,2]. The stilted buildings clearly represent the folk customs, and the artistic, cultural, and aesthetic preferences of the Tujia.

The stilted buildings in the Peng Family Village (Pengjia Village) in the mountains in Xuan'en County in the west of Hubei Province are the most typical representatives of such buildings [3]. The village is not easy to reach, and they are preserved in perfect condition due to their remote location. During the summer holiday of 2012, a team from Huazhong University of Science and Technology (HUST) surveyed the cluster of ancient stilted buildings hidden in the remote mountains in order to reveal the mystery of the Tujia Village.

2. Site Selection

The site selection of Pengjia Village represents the most intact cultural and building practices of all Tujia villages. There are more than 200 villagers in the 45 households in Pengjia Village [4]. Most of the villagers emigrated from

Hunan to Hubei Province by following the Youshui River, the most important river west of Hunan and Hubei Province. Most of the Tujia people live along the Youshui River, which they refer to as their "mother river" [5] At the end of the Qing Dynasty and during the 18th to the 20th centuries, the river was employed as the most important channel to transport salt from Sichuan Province to Hubei and Hunan Province [1]. Today, many elderly people still remember their experience of shipping salt to Pengjia Village. In the 200-year period when transporting salt was a major enterprise, there have been a few waves of immigration, which resulted from the growing population in the region. The immigrants maintained a primitive and self-sufficient way of life through farming and weaving; they lived in a closed region with little exchange and communication with the outside world aside from salt transport.

Along the banks of the Youshui River are more than a dozen Tujia villages such as the Wang Family Village, Zeng Family Village, Luo Family Village, Wu Family Village, and Baiguoba Village. The salt shipping and production are not only the pillar industry of the Tujia people, but also result in the popularity of the stilted buildings in this region.

Most importantly, the Peng Family Village has fostered the most beautiful and well preserved stilted buildings of the Tujia. The village lies on the south of the so-called Lotus Seat of the Goddess of Mercy (Kwan-Yin) at the foot of Kwan Yin Mountain. On the west of the village is a deep and long stream, over which there is a century-old wind-rain bridge (a local style of bridge that has a small structure built on the bridge to avoid wind and rain). The clean and transparent Longtan River (one of the tributaries of the Youshui River) flows through the village in its front section. On the Longtan River is a 40-meter-long and 0.8-meter-wide wood-board-paved cable bridge connecting the village to the outside world. Behind the village are steep hills and mountains covered by dense bamboo forests. Walking downstream along the Longtan River, you will witness the Lion Rock, Shuihong Temple and another village called Wangjia Village. The Pengjia Village and Wangjia Village both emigrated from Hunan province (**Figures 1-3**).

Viewed from afar, one is easily overwhelmed by the artistic glamour of the exquisite cluster of stilted buildings of the Peng Family village. Over nine buildings on piles stand on the front and rear sections of the village, which feature cornices, rake angles and traditional Chinese exterior decorations. There are also another dozen pillar-supported dwellings at the end of the stilted buildings closest to the mountain. The space in the pillars is used as a passageway, warehouse, or stables and pens for cows and pigs. Most of the stairways and courtyards in the village are paved with precisely cut and well-maintained local slate. The stilted buildings and space in the courtyards are quite well-ventilated without the odors of the adjacent stables [6,7]. Even in summer, they provide a cool and dry environment, which is perfect for the moist and hot summer climate in western Hubei Province.

Figure 1. Distant view of the cluster of stilted buildings picture by Kui Zhao, 2013.

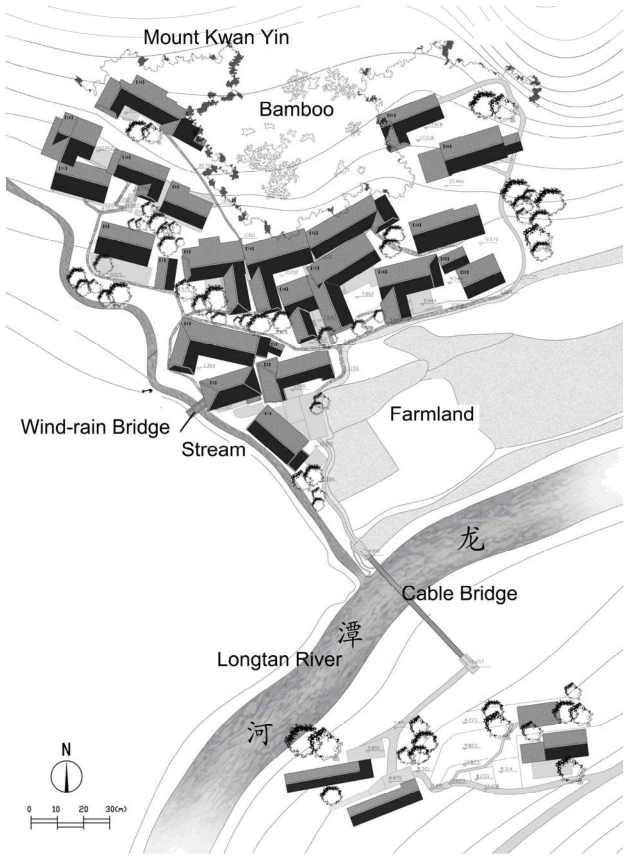

Figure 2. Site plan of Peng Family Village picture by Kui Zhao, 2012.

Figure 3. Stilted buildings of Peng Family Village drawing by Kui Zhao, 2012.

The Peng Family Village was built in front of the mountain, close to the water. The streams flowing on its sides form the borders of village. With the square shape, the village is the typical site selection of the Tujia people settlements.

3. Structural Features of Stilted Buildings

The stilted building is a kind of structure of through type timber frame that adapts to the topography in the mountain areas. Since there is an empty space in the lower level or slope of the hillside, the space is supported by many wooden columns that form the corridors under the huge roof and overhang balcony. The outmost columns are slender woods that are suspended from the roof and do not reach the ground. It seems that all the buildings are suspended by slender wood, which is the reason why they are called stilted buildings. Though different from the ordinary pillar-supported buildings, the stilted buildings can still be labeled as special pillar-supported ones. We will explain the structural differences by taking as an example, the 3-dimensional anatomy model of a stilted building with the quasi-pavilion (**Figure 4**).

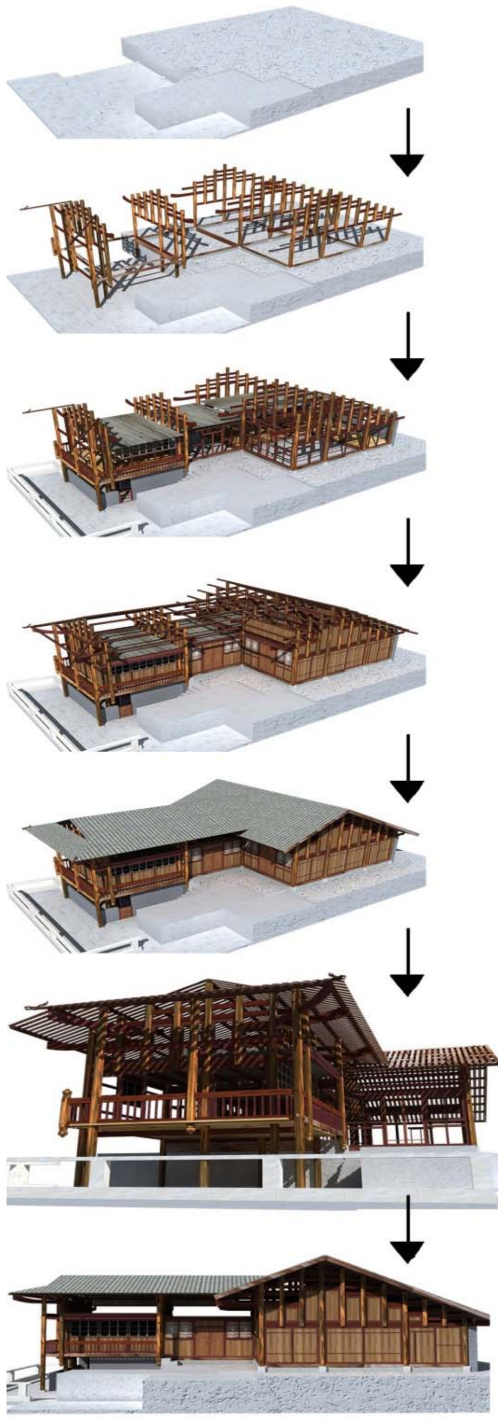

Figure 4. Construction process analysis computer modeling by Kui Zhao, 2007.

This stilted building is shaped like the letter L. It has the typical typology composed of one principal house and one wing. The foundation of the wing is lower than that of the principal house, and the lower level of the wing is suspended to form the quasi-pavilion. Some peripheral columns supporting the quasi-pavilion are not rooted on the ground. These columns are called step-supporting columns or suspension columns, whose weight is supported by the beams among the peripheral columns sitting on the floor or by the extrusions among the side columns [6,7]. The beams in the periphery of the quasi-pavilion are paved with wood boards to form the suspended corridor, at the end of which are the suspended short columns as the support of the corridor railing. These supports are called “Shuaqi”. “Shuaqi” not only act as a support function, but also play an important role in decoration. The “Shuaqi” and the head of the suspension peripheral columns are shaped like balls or pumpkins, known as “head of Shuaqi” or “golden melon” by the local people. Because of their adjacency proximity to persons’ viewport, the “golden melon” is one of the most important structural components of the decorations of Tujia buildings. The exterior sections of the square beam beyond the peripheral columns are called the “overhanging beams”, which support the cornices. Because the cornice in the stilted buildings is often quite large, the supporting beams usually have two layers, forming the double-beams structure. The upper beam of smaller size is called the secondary beam, with the lower beam supporting the majority of the weight; thus it is called the primary overhanging beam. The primary beam often uses the naturally-bending trunk of large trees for the sake of weight holding. Sometimes the primary beam is shaped like a broadsword or a horse head. Thus, it is often called the “broadsword beam” or “horse head beam” [8]. The size and bending of the primary and secondary beams are significant for the gradient of the roof and design of the cornice (**Figure 5**).

Some Tujia buildings have transformed the double-beam structure into the “short-pillar structure” by adding a “short-pillar” on the overhanging beam, which the local people call a “stool pillar” [10]. On the ends of stool pillars are purlins that support the weight of the cornices. The primary overhanging beams go through the short-pillar and transmit part of the weight to the secondary small beams. Thus, the double beams and the short pillars collaborate to form a “stool pillar” to take more weight than the double beams do, making the force more rationally arranged. There are many other kinds of tectonic evolutions based on “double beams” and “stool pillar”, such as “oblique beam” and “double pillar” [9, 10]. These designs have made the structure complex. Just like the “heads of Shuaqi”, the ends of the “stool pillars” are shaped in different designs and become the important decorations in Tujia buildings (**Figures 6** and **7**).

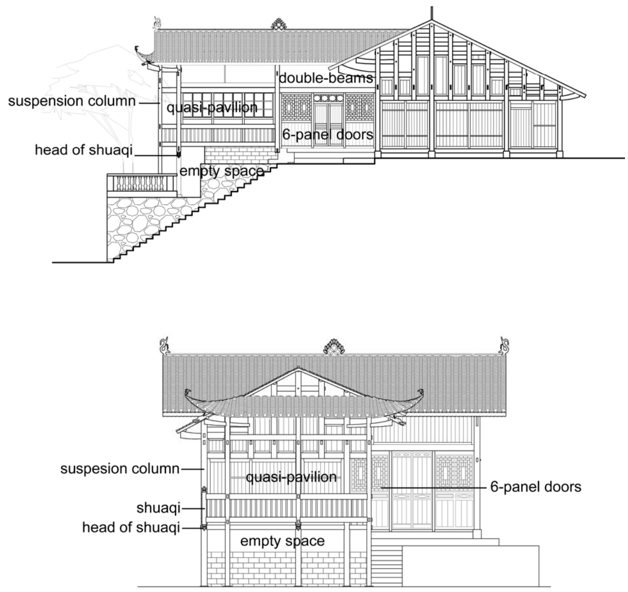

Figure 5. Façade map of the stilted building drawing by Kui Zhao, 2013.

The quasi-pavilion, suspension peripheral columns, double-beams, stool-pillars, Shuaqi, handing columns, heads of Shuaqi and ends of hanging columns have become the most evident symbols of stilted buildings of the Tujia. The most distinctive scene of the stilted buildings in Pengjia Village is the row of quasi-pavilions along the foot of the mountain, presenting the most attractive and unique features of these buildings. Additionally, the cornice on the roof of the quasi-pavilions, catering to the elevation and light quality of the buildings, extrudes upward on the four corners and seems to be flying. These designs have made the façade highly animated and are typical of the Tujia buildings.

4. Details in the Buildings

4.1. Windows and Doors

The windows and doors in the stilted buildings in Pengjia Village are one of their most attractive features as serve as a tangible symbol of the Tujia people’s wisdom and diligence in craft [10]. Though they are not as sophisticated and dignified as the windows and doors of the houses in Anhui Province, they are still known for their ancient, profound and diversified style, presenting the most delicate example of Tujia craftsmanship (**Figure 8**).

Most of the Tujia doors to the principal sitting room have six door panels that are 2.8 meters high and 5 meters wide. These six door panels, installed via the door spindles, form three doors to the room. The ends of each panel have the penetrating or relief flower-shaped

Figure 6. The decorations of stool pillars picture by Kui Zhao, 2011.

sculptures. In the middle section of the panel are the door windows of various designs. The 6-panel doors are sometimes fake. The genuine 6-panel doors can be opened forming three passages for people of different age and status in the family. During the Spring Festival when the villagers play the "lion lantern" [9,10], if the team fails to enter the doors following the proper etiquette, they will find it difficult to leave the room. The fake 6-panel doors, though they also have the same structure, have the panels on the sides simply fixed and not operable, leaving only two doors in the middle that can be opened. Some villagers would install two smaller door panels beside the 6-panel doors for the passage of chickens and dogs. The smaller door is 1.1 meter high and 1.7 meter wide. It is made of the timber of the *Cedrela chinensis* or "nut tree" [11,12]. Owing to the safe environment in the village, some houses are not equipped with the 6-panel doors and only have the smaller doors.

The secondary room is often equipped with only one wooden door with two panels. The other rooms use the single-panel door. There are two types of single-panel doors. One is the "embedded door" [9,10]. When closed, the door panel is perfectly imbedded into the door frame. The other is the "bang door" [9,10], because the door panel is larger than the door frame, and it will produce a "bang" noise when closing the door, which often results in the clash between the door panel and frame.

The windows are obviously used for lighting and ventilating; however, the windows in Pengjia Village have been given cultural content by the Tujia carpenters. These windows are shaped like Chinese characters. The door windows are shaped in a rectangle while the wall windows are square. The window designs are often symmetrical horizontally or vertically. The carpenters often make drawings first, then construct 3-cm patterns in a tenon-and-mortise design and connect the patterns to form the windows.

The window design reflects the craftsmanship and individuality of the Tujia carpenters and represents the pursuit of the Tujia people for a happy life. Every window design made of the patterns has its own meaning. Some carpenters even shape the patterns into sophisticated designs or animals. These designs are vivid and captivating even to those who do not understand their precise cultural meanings.

Unfortunately, there are only a few carpenters left in Pengjia Village who are trained in these traditional techniques. The owner of the house where our team lived was just such a carpenter. He lamented the loss of window carving techniques, saying most of the carpenters today have failed to inherit the traditional techniques and skill. Old carpenters make the windows with their own hands, but this distant village in the depth of mountains has been greatly influenced by the modern technologies. The young carpenters today mainly use machines to cut the battens, which are uniform in size and shape. However, when we measured the structural components of the ancient buildings, we found some components had different

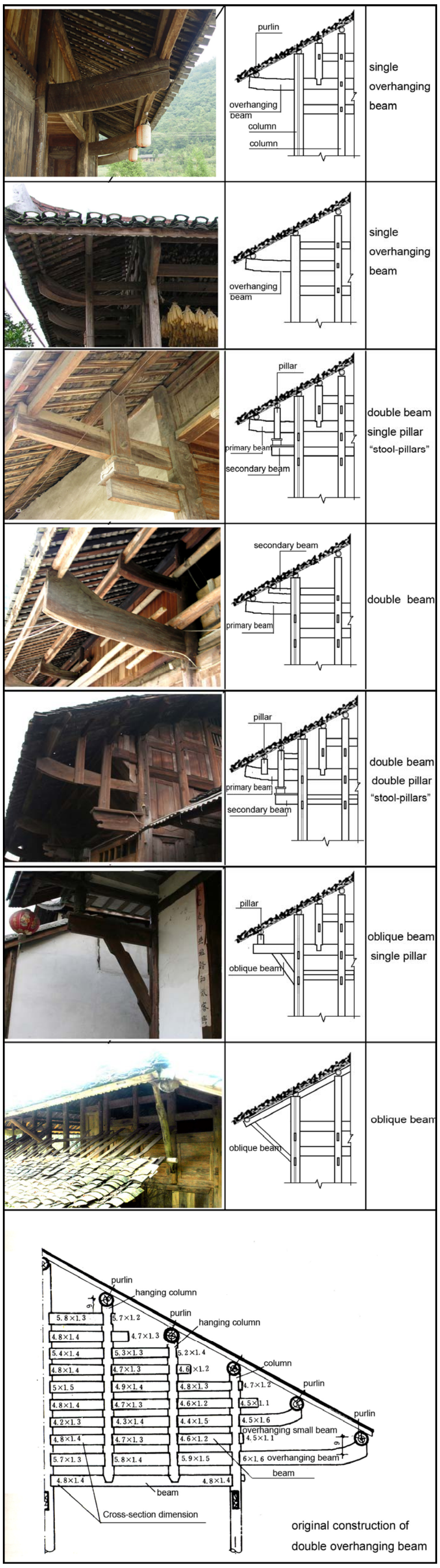

Figure 7. Tectonic evolution of double-beam structure; photo & drawing by Kui Zhao, 2008.

Figure 8. The real 6-panel door, the fake 6-panel door and the single-panel doors picture by Kui Zhao, 2007.

sizes. Probably the aesthetic attractiveness of the artisanship cannot be realized by the components made by the machines.

4.2. Roof

The building roofs in the Tujia villages produce an exquisite flowing visual effect. Seen from the vertical exterior layout, the buildings form the anatomy featured by touching the sky but staying away from the floor and the even top level but uneven floor level [11,12]. Such section planes are formed by adopting the techniques of suspended roof, omitted levels, and overlapping levels. As a result, viewers will sense the lively and vivid feeling without dullness or rigidity. The roof of the single stilted building is not complex in itself. It is often shaped like "—" or "L". Sometimes, the huge dark grey roof, the significant cantilever of the cornice, and the suspension space in the lower level will form the unstable composition of "heavy head and unstable feet". When the numerous facades are viewed in a cluster, however, the buildings become balanced, solemn, elastic, and rhythmic, producing a generous and profound aesthetic sense. If we see the overall layout of the Tujia stilted buildings, we will find them in an irregular and elastic cluster. Some houses are built catering to the topography of the mountain. Some produce overlapping layers of structure. Others are built on the edge of valleys. Many are lively and vivid, and a select number are sublime because of their positions on the hilltop.

Most of the stilted buildings in Pengjia Village are built at the foot of the mountain or hill. The narrow space under the cornices and the stairways following the ups and downs of the topography often produce the atmosphere of suddenly a village emerges in the eyes when people are wondering whether they have lost the directions [13,14]. Because of the large height difference in the site area, the large roof of the front building often surrounds the outdoor terrace of the rear building. Looking down from the suspended balcony of the higher building, you can see the overlapping and continuous roofs, looking like a rolling hill. These roofs seem to be surrounded by a crystal stream, a suspension bridge, yellow farm fields, and a huge, green mountain, which form fantastic rural scenery (**Figure 9**).

Figure 9. Roofs view of the cluster of stilted buildings picture by Kui Zhao, 2013.

4.3. Shrines

The Tujia buildings are cohabited by human beings and immortal beings [16,17]. The Tujia people must locate space in their homes to worship the immortal beings and their ancestors. These spaces are often set in the shrines or places equivalent to shrines, in the principal sitting rooms. Often sacred spaces are placed in the kitchen. People also believe that the immortal beings live in the stables, mills, workshops, or corners in the house [16,17]. In addition, different ethnic groups allocate different spaces in the house as shrines and adopt different functions and shapes for the shrines, which become an important symbol identifying the ethnic group (**Figure 10**).

The shrines in the Peng Family Village are often placed on the rear wall in the principal sitting room, in the middle of which is installed a wood board called a "shrine platform" to worship Grandfather Nuotuo and Grandmother Nuotuo believed to be the ancestors of Tujia people [15]. On the platform are placed the incense burner, candles, and straw paper. On the top of the shrine is another piece of wood board called a flame board, used to prevent against fire. Apart from the above-mentioned hardware in the shrine of the Tujia buildings, there is also the ancestral list describing the hometown and name of the ancestors pasted on the middle of the platform and the flame board. After everything is set, the priest of the Tujia people will be invited to hold ceremonies to usher in the immortals beings or ancestors into the shrine. After this ritual is completed, the space becomes a genuine shrine.

5. Spatial Features of the Buildings

The Tujia villages have the distinctive spatial forms composed of the narrow lane space in the village, the space under the cornices and the courtyard space surrounded by the roof, and the building and the environmental space beyond the village.

Figure 10. Shrine picture by Kui Zhao, 2007.

The villages of the Tujia people are often built on the river with a certain distance from the river; this distance can provide the buffer area when the flood comes. In addition, the farmland in the buffer area is fertile and becomes an excellent growing place for crops. The entrance roads to the villages are also built on the south bank of the river, making the river the natural protection for the villages. The sequence of the village layout is composed of the hill roads, river, suspension bridge, farmland, village, bamboo forests, and mountain in the background. Such a spatial layout has formed the diversified and complex exterior space of the village.

Walking into the village, crossing the winding lanes and stepping onto the stairways, you will enter the compact and diversified space in the single stilted buildings.

The stilted buildings have many forms; "—" shape, "L", and "U" shape are very popular. The Tujia people choose different styled dwellings according to the complex changes of the topographic landforms. They usually build dwellings parallel to the contour line of the mountain or hill, but still, many stilted buildings are built vertical to the contour line because of the limited site area in mountain rural area. The typical stilted building can be divided into two parts: one is set on a higher level, another on a lower area. The residential area in higher level has the sitting room and bedroom, and vertical to it is the suspended building. The suspension space in the lower level has the toilet, bathroom, and pigpen. The second floor, which connects to higher areas, has the dining room, kitchen room and another bedroom. By taking some typical stilted buildings in Pengjia Village as an example, we summarize their spatial features as follows (**Figures 11** and **12**).

Every building has many rooms, and every room is linked to each other. The sitting room is the most important space, which has many doors on the walls in each

Figure 11. Analytical model of the single stilted building Modeling picture by Kui Zhao, 2010.

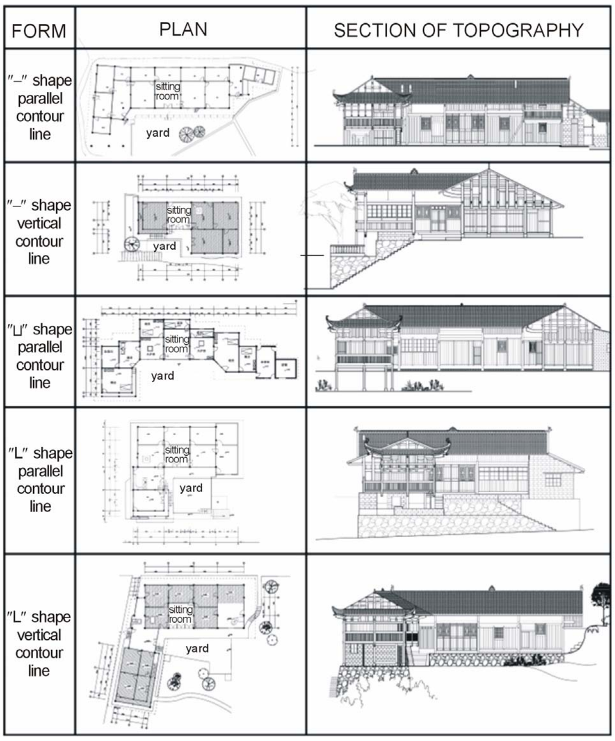

Figure 12. Analysis of plane and section of stilted building drawing by Kui Zhao, 2010.

direction. The other private rooms, such as the bedroom, often have two doors that provide access to it. It represents that the family is cohesive but does create an ambiguous awareness of privacy.

In winter, people flock together around a brazier (which is a large braze container in which charcoal is burned) in the center of the sitting room. Under the sitting room floor is empty, so the warm air flows into the empty space keeping the inside room warm. It is a simple but efficient folk technology (**Figure 13**).

Sewage is strictly separated from the hygienic areas. To make better use of the space in lower level, the stable and toilet that produce odor and sewage are often placed in this level. Thus, the wood structure of the higher level can remain dry and hygienic for the whole year. The stilted buildings also separate the inhabitants from the many insects and poisonous snakes living on the hill slopes. The courtyard serves as the transit space for transport of goods. The rooms are arranged on the hill slope, and consequently, they may not be reached by directly by walking. The courtyard is often used as a temporary storage space. The 2 meters wide stone paving is beyond the extended cornice, and the cornices are used as the shelter against rain and strong sunlight when people walk on them.

Figure 13. warm floor in sitting room picture by Kui Zhao, 2013.

6. Conclusions

The Tujia people's stilted buildings have their own ethnic distinctiveness in construction, such as the quasi-pavilion, suspension peripheral columns, double-beams, stool-pillars, and huge roof, balcony and cornices. The most distinctive feature is that many wooden pillars, which help the inhabitants adapt to living in mountain environment, support the buildings. High above the ground, stilted buildings have the following advantages:

First, it can keep people away from deadly dangers, such as miasma, poisonous vegetation, venomous snakes, and huge wild animals.

Second, people can stay away from the humidity close to the ground and prevent humidity related diseases.

Finally, there is better lighting upstairs, so people can work on delicate handcrafts or simply enjoy the light.

The Tujia people also create their own architectural decorative art: "Shuaqi", handing columns, heads of Shuaqi and ends of hanging columns, 6-panel doors, and carved patterns windows. All of these have become striking characteristics of the stilted buildings of the Tujia people.

The carefully preserved stilted buildings in Pengjia Village have inherited the traditional features of the Tujia people's architectures. Based on a large number of our first-hand information through field research, ancient architecture surveying, and mapping in this village, in combination with our research in the Tujia areas over the past decade, the paper aims to record the real history and keep the local art and traditional technology.

Since the end of last century, rapid economic development in the past 20 years in China has resulted in the introduction of cheap undifferentiated concrete buildings in the Tujia area. Residents are faced with financial and natural resources challenges such as decreasing forests continuous rise of timber prices, and the rapidly dwindling number of skilled wood workers—conditions that force them to abandon traditional buildings. Additionally, the existing wooden structures need regular maintenance, such as having tiles replaced and being brushed with tung oil. Since large populations are migrant workers, many of the houses on stilts become empty nests. Without proper care, the stilted houses naturally collapse very easily. This constantly required care is what makes people give up on the stilted buildings. Local residents now tend to build simple concrete buildings with low costs rather than stilted buildings with complex wooden structures, thus the regional characteristics of the Tujia architecture are gradually disappearing.

In the past five years, highway extensions and railway construction have brought large number of tourists to the Tujia area [15,17]. Visitors revel in the beautiful natural scenery, while simultaneously marveling at these stilted building clusters integrated with the landscape. This has led the government to focusing on the return of traditional building methods in an attempt to attract more visitors in order to meet the tourism demands and promote economic development in the Tujia villages such as Pengjia.

For example, starting in 2008 in the EnshiTujia Autonomous Prefecture, Hubei Province, the government began to restore the stilted buildings gradually from three aspects to maintain the rural traditional regional characteristics.

The first priority is to protect the integrity of ancient villages, such as the Pengjia Village, as articulated in this paper. Our team for example has performed measured drawings, photographed every ancient building in the village, established original files for them, set up protection signs, and stationed protection mechanisms to protect the village. Demolition, reconstruction, and new building construction are strictly prohibited in the ancient village, and special funds will be allocated for the repairing and reinforcement of these irreplaceable cultural resources. To protect the ancient architecture, special attention has also been paid to the village environment and village culture, e.g., the restoration of riverine and mountain vegetation, and support of the traditional dances and customs of Pengjia Village as intangible cultural heritage. Such examples include the "Hands Waving Dance", "Drum Melody for Weeding", and "Xuanen Play". Tourists are invited to participate in the dances to experience the true traditional culture and meaning of the dances (**Figure 14**).

The second priority is to construct new buildings in the traditional way. The construction of new villages and expansion of existing villages in Tujia area require planning and construction following traditional ideas, which is completely out of the ordinary compared to commercial development modes. Planners need to extract and recombine traditional elements based on meticulous research on traditional Tujia villages (such as the windows, doors, roof, balcony, shrines and other elements as mentioned in the paper) and cooperate with the traditional woodworkers. For example, our research team has made numerous explorations and conducted various experiments in the design of the Pengjia Village Visitor Center, Qingyang Dam Ancient Village Renovation, Yumuzhai Ancient Village Planning (**Figure 15**). In addition, we highly encouraged the local residents to participate in together with the Tujia building construction professional team. Using these approaches, we hoped to encourage the residents to consciously build and maintain the traditional wood structure buildings. In the meantime, the local government pays subsidies on the increased cost causing by building the complexity of the stilted buildings.

The third priority is to restore and apply the traditional style onto discordant architecture. The local government describes it as "dressing up" the building, and this is mainly targeted at the large number of newly built rough concrete buildings at the end of last century. People have begun to add wooden roof structures at the top of the concrete structure, fitted them with wooden battens for the exterior wall, replaced the concrete balcony railings with suspension columns, Shuaqi, and head of Shuaqi used in the balcony of Tujia people, and replaced the aluminum alloy doors and windows with unique Tujia six-panel doors and bang doors. With this treatment, the exterior of the buildings that cannot be removed now has a traditional cover and is harmonious with the surrounding ancient villages (**Figure 16**).

We are applying our research through active involvement in the protection of settlements with Tujia characteristics and construction practices. The purpose of this ongoing initiative is to preserve the regional characteristics

Figure 14. Protection of traditional buildings and folk customs picture by Kui Zhao, 2011.

Figure 15. Directing Tujia people to build new stilted buildings using authentic traditional techniques picture by Kui Zhao, 2010.

Figure 16. "Dress up" the discordant architecture picture by Kui Zhao, 2011.

of Tujia buildings and to help the international community understand the unique architectural forms of this ethnic group in inland China.

Ultimately, it is the inherent beauty of traditional Tujia architecture that demands that we share this research to protect and preserve the Tujia villages for future generations.

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Quality Study of Automated Machine Made Environmentally Friendly Brick (KAB) Sample Using Film Neutron Radiography Technique

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ABSTRACT

Neutron radiography (NR) technique has been adopted to study the internal structure and quality of the KAB bricks made by Hoffman kiln method. Thermal neutron radiography facility installed at the tangential beam port of 3 MW TRIGA Mark-II Research Reactor, AERE, Savar, Dhaka, Bangladesh is used in the present study. Measurements were made to determine the internal structure and quality of the automated machine made environmentally friendly brick sample. In this case, optical density/gray values of the neutron radiographic images of the sample have been measured. From these measurements, the porosity, water penetrating height, water penetrating behavior, initial rapid absorption of water (IRA), elemental distribution/homogeneity and incremental water intrusion area in the sample have been found. From the observation of different properties, it is seen that, homogeneity of the Hoffman kiln brick KAB is not perfectly homogeneous and contains small internal porosity; the incremental water intrusion area is very poor, and the water penetrating height through the two edges is higher than the middle part; the initial rapid absorption (IRA) rate is also very poor and the water penetrating behavior of the samples is different as like as stair, capillary, wave and zigzag shape. From these points of view, it is concluded that the quality of the environmentally friendly brick KAB is better. The results obtained and conclusion made in this study can only be compared to the properties of bricks produced under similar conditions with similar raw materials.

Keywords: Neutron Radiography Technique; Water Penetrating Height/Behavior; IRA

1. Introduction

Neutron Radiography (NR) is a technique of making a picture of the internal details of an object by the selective absorption of a neutron beam by the object. NR uses the basic principles of radiography whereby a beam of radiation is modified by an object in its path and the emergent beam is recorded on a photo film (detector). In general, the radiography technique is nothing but a simple process of exposing some objects to an X-ray, gamma-ray, neutron beam and some other types of radiation and then attenuated outgoing beam from the object is passing through a special type of photographic film to form images of the objects on the radiographic film or detector. Also it is called a non-destructive testing (NDT) [1] and evaluation technique of testing non-nuclear and nuclear materials and industrial products. NR is an imaging technique which provides images similar to X-ray radiography and complementary technology for radiation diagnoses. Neutron radiograph gives the information of the internal structure of an object; it can detect light elements, which have large neutron absorption cross-sections like hydrogen and boron; it is completely complementary to other NDT techniques, like X-ray or gamma-ray radiography. The atoms of the object material scattered or absorbed the radiation and so the beam reaching the detector shows an intensity/gray value pattern representative of the internal structure of the object [2]. Any in-homogeneity in the object on an internal defect (such as voids, cracks, porosity, inclusion, corrosion etc.) and morphological change in the plant pod seeds [3] will show up as change in gray value/radiation intensity reaching the detector. Under these techniques, detecting faults in neutron shielding materials, flow visualization: real time neutron radiography, quality control of explosive devices, defects in ceramics materials, aircraft component, surface corrosion on aluminum, medical and biological applications, investigations of the root soil system, migration/rising of water in various building products/building materials, physical description of water transport in a porous matrix of the sample material, density fluctuations and porosity detection in ceramics etc [4-20]. Clay is a widely available raw material that survives very well in its fired form. Clay brick has been found in the ruins of ancient civilizations [21]. Bhatnagar *et al*. saw that properties of these bricks are affected as a result of physical, chemical and mineralogical changes [22,23]. Mbumbia *et al*. investigated that compressive strength and water absorption are two major physical properties of brick that are good predictors of bricks ability to resist cracking of face [24]. Few scientists studied that compressive strength is highly affected by firing temperature method of production, and physical, chemical and mineralogical properties of the raw material [22,25]. Water absorption is a measure of available pore space and is expressed as a percentage of the dry brick weight. It is affected by properties of clay, method of manufacturing and degree of firing. Some of the researchers studied that firing shrinkage increases with higher temperatures [26]. The quality depends on the firing temperature and firing time also. Decreasing firing temperature and shortening firing time do not only reduce the cost of production but also increase the productivity of the factory.

Environmental concerns have been raised in some parts of the world where coal is the main power generating sources and where bricks are also the main building material. Most of the scientists believe that fly ash on its own can be an excellent raw material for brick making. This has now been proven and a patent is taken for the manufacture of bricks from fly ash [27].

Many ancient cultures have made useful decorative items such as pottery, figurines, building tiles, and burial containers that become important parts of the archaeological record. The material aspects of clay and ceramic technology, the physical properties of clay and various firing methods can be investigated using archaeometric techniques [28,29]. Properties of bricks are affected as a result of physical, chemical and metrological changes [23,30]. Water absorption is a measure of available pore space and is expressed as a percentage of the dry brick weight. It is affected by properties of clay, method of manufacturing and degree of firing. Water absorption capacity of the brick affects the surface finishing of the brick-laid wall [21,26,31]. Ancient technologists and archaeological material researchers have employed standard techniques such as X-ray radiography, X-ray diffraction (XRD), scanning electron microscopy (SEM), and neutron activation analysis (NAA) to study structure and composition of ceramic materials [28,29]. Neutron radiography has been used to detect internal defects in some materials such as ceramics [9], tiles [10] and different building industries [11]. The technique is also adopted for the study of water absorption behavior in biopol, jute-reinforced-biopol composite [12] and wood plastic composites [13] etc. In the present work, neutron radiography technique has been adopted to the determination of elemental distribution/homogeneity, porosity, incremental intrusion area of water/water penetrating height and penetrating shape/behavior, and initial rapid absorption (IRA) of water in the sample as well as the quality of automated machine made environmentally friendly KAB brick.

2. Experimental Facility

The experimental neutron radiography facility installed at the tangential beam port of 3 MW TRIGA Mark II reactor in the Institute of Nuclear Science and Technology, Atomic Energy Research Establishment, Savar, Dhaka, Bangladesh. The neutron radiography facility consists of the following devices/equipment.

2.1. Bismuth Filter

In the NR facility at TRIGA reactor of BAEC a 15 cm long Bi filter in the tangential beam port is used to reduce the intensity of gamma ray significantly from the beam to prevent the unwanted fogginess in the radiographic image.

2.2. Cylindrical Divergent Collimator

A cylindrical divergent collimator made of 120 cm long aluminum hollow cylinder with 5 cm and 10 cm diameter at the inner and outer end, respectively, has been inserted in the tangential beam port to collimated neutron beam of the reactor. The advantage of the divergent collimator is that a uniform beam can be projected easily over a large inspection area. Collimators are required to produce a uniform beam and thereby produce adequate image resolution capability in a neutron radiography facility.

2.3. Lead Shutter

The outer end of the tangential beam tube is equipped with a lead-filled safety shutter and door to provide limited gamma shielding. The thickness of lead in the shutter is 24 cm and the diameter of the shutter is 33 cm.

2.4. Beam Stopper

A wooden box with dimension of 68 cm × 40 cm × 68 cm has been made with the attachment of four ball bearings on the bottom part of it for forward and backward movement in front of the tangential beam port. It looks a wooden box, which contains neutron-shielding materials like paraffin wax and boric acid in 3:1 ratio by weight for neutron shielding.

2.5. Sample and Camera Holder Table

There is a sample and camera holder table with both horizontal and vertical movement facility placed in front of the beam line.

2.6. Beam Catcher

To absorb transmitted and scattered neutron and gamma radiations a beam catcher with dimension 100 cm × 100 cm × 85 cm has been placed behind the sample and camera holding table. A 30 cm × 30 cm × 30 cm hole has been made in the middle of the front face of the beam catcher which coincides with the central axis of the beam port. A 30 cm × 30 cm × 15 cm lead block weighing 125 Kg has been placed at the back side of the hole for gamma shielding. For neutron shielding a mixture of paraffin wax and boric acid has been used in the catcher. The total weight of the beam catcher is 968 Kg.

2.7. Biological Shielding House

The emitted neutron and the gamma rays are extremely dangerous for human body. This is why, to prevent these harmful rays to spread over the entire environment a biological shielding house has been built around the NR facility of the tangential beam port. It is made of special concrete containing cement, heavy sand (magnetite, ilmenite and ordinary sand) and stone chips in the ratio 1:3:3. Paraffin wax and boric acid in 3:1 ratio by weight were also used inside the biological shielding wall for neutron shielding. The width and height of the biological shielding wall of the facility are ≈ 3.0 ft and 6.5 ft, respectively. Details of the NR facility can be found elsewhere [3,32,33]. The schematic diagram of the neutron radiography facility of 3 MW TRIGA Mark II Reactor, AERE, Savar, Dhaka is shown in **Figure 1**.

3. Experimental Procedure

3.1. Collection, Preparation and Size of the Sample

Sample has been collected from Kapita auto bricks limited located at Joypura, Dhamrai, Dhaka, Bangladesh.

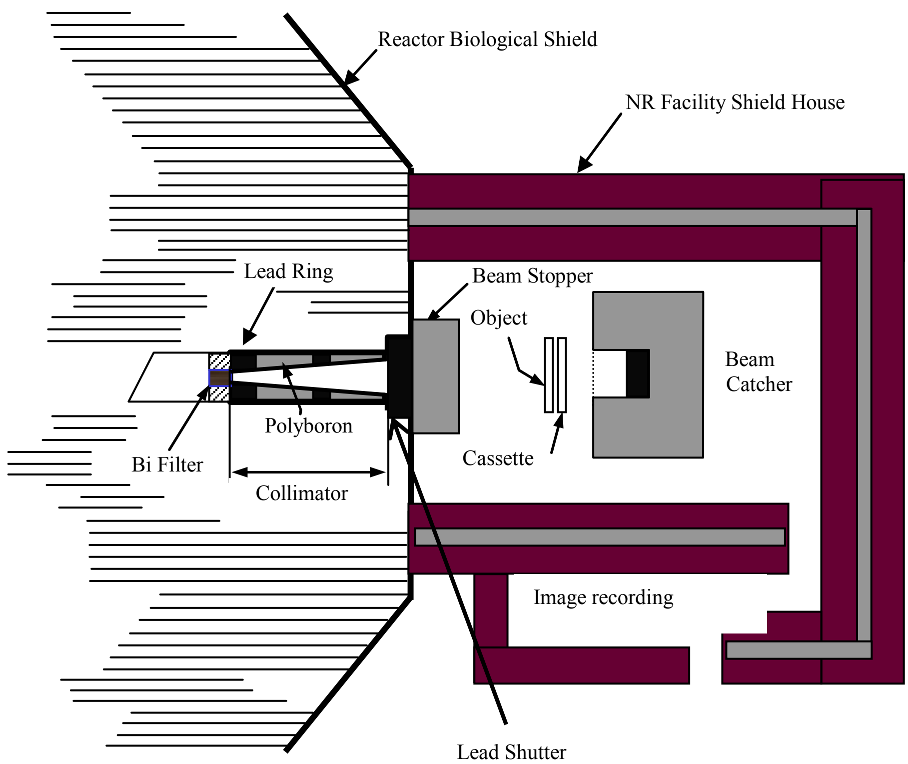

Figure 1. Schematic diagram of the neutron radiography facility.

For final preparation, the sample is polished manually by using series paper, cement block, diamond cutter, and then the sample was dried at daylight/dryer machine until to get the constant weight. The sample is the rectangular shape and its size is 23.000 × 11.360 × 6.540 cm^3 and 23.050 × 10.821 × 6.480 cm^3 for KAB 1 and KAB 2, respectively. In the case of KAB 2 sample, coal is mixtures with the soil and this coal is used to burn it. But in case of KAB 1 sample, coal is used into the brick kiln to burn the sample.

3.2. Loading Converter Foil and Film in the NR Cassette

A thin converter (gadolinium metal foil of 25 μm thickness) was placed at the back of the X-ray industrial film. The loading of the X-ray industrial film (Agfa structurix D_4DW) into the NR cassette (18 cm × 24 cm) is a simple procedure [14]. There are a number of steps to place the industrial X-ray film into the NR cassette to protect the film against daylight and lamplight.

3.3. Placing of Sample and the NR Cassette

The sample is placed in close contact with the NR cassette and directly on the sample holder table. The NR cassette is placed on the cassette holder table. Both of NR cassette and sample are placed in front of the neutron beam having 30 cm in beam diameter.

3.4. Determination of Neutron Beam Exposure Time

Exposure means passing of neutron beam through a sample and holding it onto a special film (X-ray industrial film) in order to create a latent image of an object in the emulsion layers of that film. Exposure time differs for different samples, depending on the intensity of the neutron beam, density and thickness of the sample and neutron cross-section. The optimum exposure time of the sample was determined by taking a series of experiments/radiographs at different exposure time, while the reactor was operated at 250 KW. For the present experiment we found the optimum exposure time is 60 minutes. The sample was then irradiated for that optimum time to obtain good neutron radiographs.

3.5. Immersion Procedure of the Brick Sample

The brick sample is placed in a plastic pan and a constant 2.0 cm height of water level is maintained. The water level is observed very carefully and adds extra water to maintain water level at 2 cm during the immersion time. After time of interest (TOI) such as 5, 10, 15 and 20 minutes brick sample take off from the pan and extra water of out side the sample is removed by using the tissue paper.

3.6. Obtained Radiographic Images of the Sample

3.6.1. Irradiation

While all the procedures (a-e) were performed, the neutron beam was disclosed by removing the wooden plug, lead plug and beam stopper from the front side of the collimator. Each sample was then irradiating for the optimum time (60 min) one by one at various immersion time.

3.6.2. Developing

Developing is an image processing technique by which the latent image recorded during the exposure of the material is converted into a silver image [34]. Developing process is completed at 20˚C for 5 minutes.

3.6.3. Fixing

When the developing is completed a conventional photographic material must be treated in an acid stop bath or it must be rinsed in water, after which it is treated in a fixation bath. The fixation solution will dissolve the unexposed silver-halide crystals leaving only the silver grains in the gelatin. The fixing is completed with in 5 minutes and controls the fixture temperature at 20˚C.

3.6.4. Washing

In between developing and fixing the radiographic film, it is necessary to wash for 1 minute at flowing tap water.

3.6.5. Final Washing

The silver compound which was formed during the fixing stage must be removed, since they can affect the silver image at the latter stage. For this reason the film must be washed thoroughly in flowing tap water for 15 minutes after completion of developing and fixing process.

3.6.6. Drying

After the final washing, the films were dried by clipping in a hanger at fresh air/or in a drying cabinet.

After developing, washing, fixing and the final washing obtained radiographic images (**Figures 2** and **3**) of the required KAB brick sample at different immersion time.

4. Mathematical Formulation

4.1. Optical Density Measurement

The neutron intensity before reaching the brick sample (object) is different from the intensity of the neutron after passing through it. The relationship between these two intensities is expressed through the following equation [15]

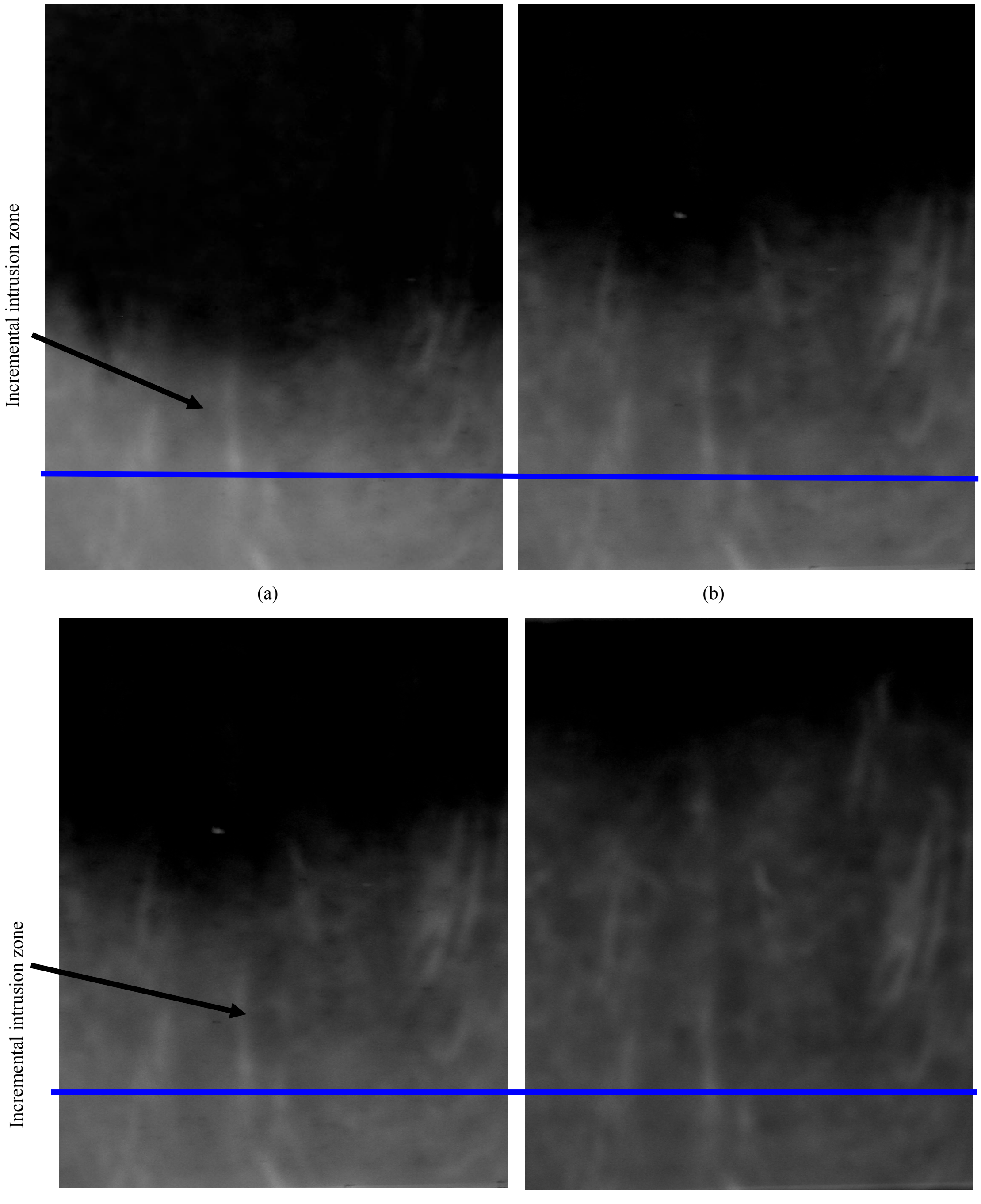

Figure 2. NR images of KAB 1 for (a) 5 min and (b) 10 min water absorption. NR images of KAB 1 for (c) 15 min and (d) 20 min water absorption.

$$I = I_0 e^{-\mu x} \quad (1)$$

where, e = base of natural logarithms, x = thickness of an object, μ = linear neutron attenuation coefficient, I and I_0 are the neutron intensity after passing through the object and the neutron intensity incident on the object, respectively.

The mathematical expression for the optical density [16] at a point of the film/NR image, D is given by:

$$D = \ln\left(A_0/A\right) \quad (2)$$

Here, A_0 = response of densitometer without the sample image and A = response of densitometer with the sample image.

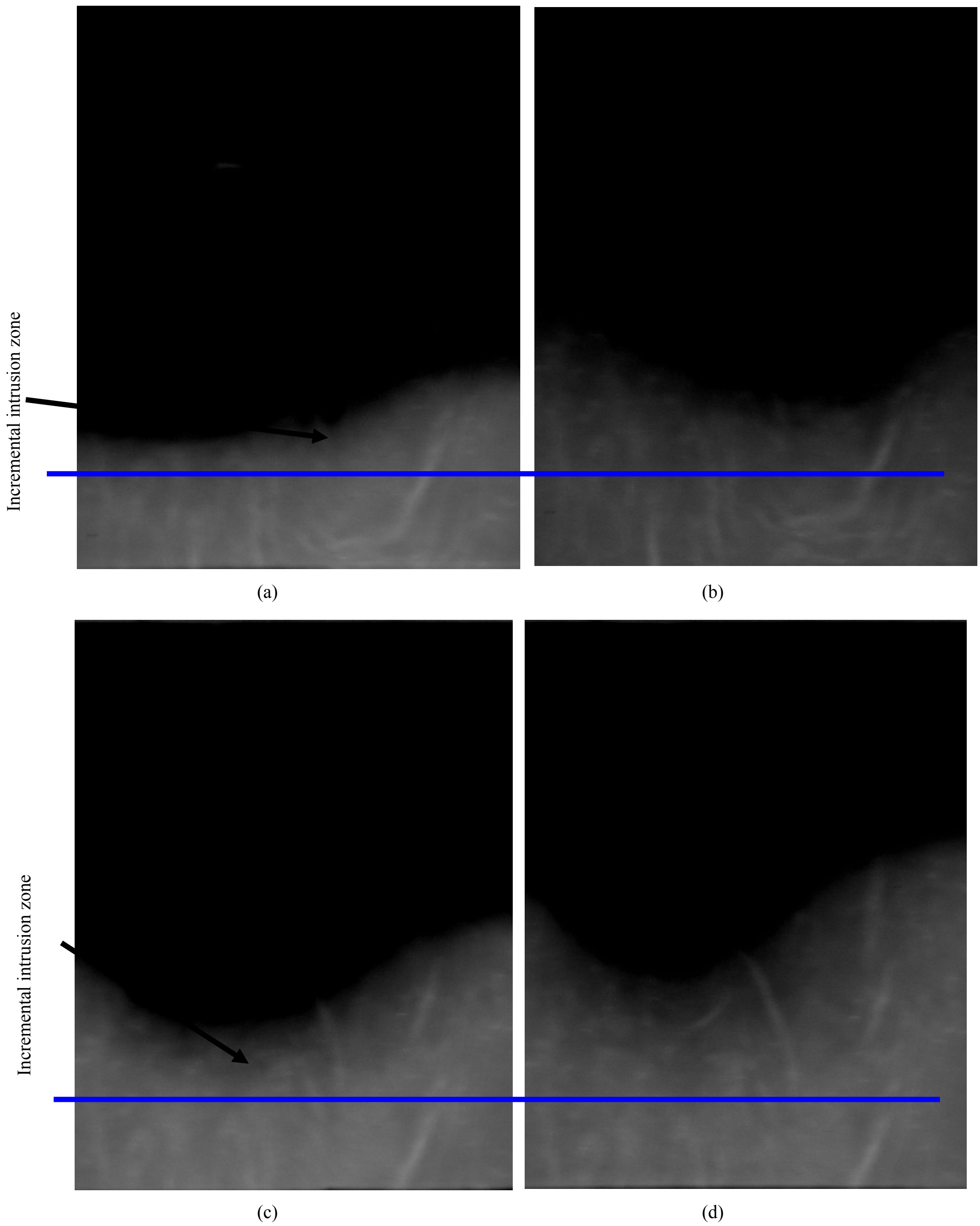

Figure 3. NR images of KAB 2 for (a) 5 min and (b) 10 min water absorption. NR images of KAB 2 for (c) 15 min and (d) 20 min water absorption.

The density of film is measured with an optical densitometer (Model 07-424, S-23285, Victoreen Inc. USA) [5]. A small beam of light from the light source passes through the film area which is measured by densitometer. On the other side of the film, a light sensor (photocell) converts the penetrated light into an electrical signal. A special circuit performs a logarithmic conversion on the signal and displays the results in density units. The primary use of densitometers in a clinical facility is to monitor the performance of film processors. Actually, optical density is the darkness, or opaqueness, of a transparency film and is produced by film exposure and chemical processing. An image contains areas with different densities that are viewed as various shades of gray.

4.2. Gray Value

The visual appearance of an image is generally characterized by two properties such as brightness and contrast. Brightness refers to the overall intensity level and is therefore influenced by the individual gray-level (intensity) values of all the pixels within an image. Since a bright image (or sub image) has more pixel gray-level values closer to the higher end of the intensity scale, it is likely to have a higher average intensity value. Contrast in an image is indicated by the ability of the observer to distinguish separate neighboring parts within an image. This ability to see small details around an individual pixel and larger variations within a neighborhood is provided by the spatial intensity variations of adjacent pixels, between two neighboring sub images, or within the entire image. Thus, an image may be bright (due to, for example, overexposure or too much illumination) with poor contrast if the individual target objects in the image have optical characteristics similar to the background. At the other end of the scale, a dark image may have high contrast if the background is significantly different from the individual objects within the image, or if separate areas within the image have very different reflectance properties.

Although the intensity distribution within any real-life image is unlikely to be purely sinusoidal, these definitions provide a basis for comparison. For example, an image that contains pixels with brightness values spread over the entire intensity scale is likely to have better contrast than the image with pixel gray-level values located within a narrow range. The relationship between the intensity spread at the pixel level and the overall appearance of an image provides the basis for image enhancement by gray-level transformation. The terms gray value and intensity are used synonymously to describe pixel brightness. Actually, the specific relationship between the shades of gray or density and exposure depends on the characteristics of the film emulsion and the processing conditions. This gray value is measured using image analysis software Image J [35].

5. Results and Discussions

In the present investigation NR techniques has been adopted to study internal defects such as in-homogeneity, porosity/voids, initial rapid absorption (IRA), water penetrating rate/behavior and incremental intrusion area of automated machine made environmentally friendly KAB bricks. Automated machine made environmentally friendly bricks industry (made by Hybrid Hoffman Kiln method) is established very recently in Bangladesh. The NR techniques allowed us to comment on the quality of this type of brick samples from the measurement of the gray value/optical densities of their neutron radiographic images.

5.1. Porosity/Voids and Homogeneity of the Samples

The quality of a brick samples depends on the proper distribution of the contents, porosity, hardiness, water absorption behavior etc. in the sample. In this section, porosity, elemental distribution of the samples has been studied by measuring gray value/intensity from the neutron radiographic images of each sample. Variation of gray values of the radiographic images of the samples indicates that the constituent components of the samples are not uniformly distributed and having internal porosity.

The **Figure 4** shows the gray value versus pixel distance plots of radiographic image of the KAB sample. The gray value has been obtained by drawing line profile of 1056 × 1600 pixel area on the radiographic images of an object. From this figure it is observed that in most of the places the variation of gray value is not regular manner for KAB 1 but in few places it is regular. It is also observed that KAB 1 sample is not perfectly homogeneous and contains little porosity because of irregularity of gray value. In the same figure for KAB 2, it is observed that variation of gray value in most of the pixel point is slightly irregular in nature. This shows that most of the regions for KAB 2 is homogeneous and small region is inhomogeneous. Small variation of gray value/intensity indicates the presence of less internal porosity of that place/area.

5.2. Water Penetrating Height at Different Immersion Time of the Samples

KAB 2

Water penetrating/rising behavior of the KAB 2 sample at different immersion time such as 5, 10, 15, 20 minutes is shown in **Figure 5**. From these graph it is observed that due to 5 minutes immersion water rises in upward direction is 2.6 cm and 4 cm through two edges and 3 cm at the middle side. In case of 10 minutes, penetrating of water at the middle place is 4 cm and through the edges this penetration is about 6 - 6.5 cm. For 15 minutes water immersion, the water uptake is 4 cm at middle and at two edges the water uptake is 6.4 - 6.6 cm. For 20 minutes, water uptake is 5 cm at middle and at two edges is 7 - 8 cm. From above investigation it shows that at first 5 minutes the water uptake through the middle is very higher than that of 10, 15 and 20 minutes. Except for first 5 minutes water immersion, water rises through the two edges is higher than the middle part.

KAB 1

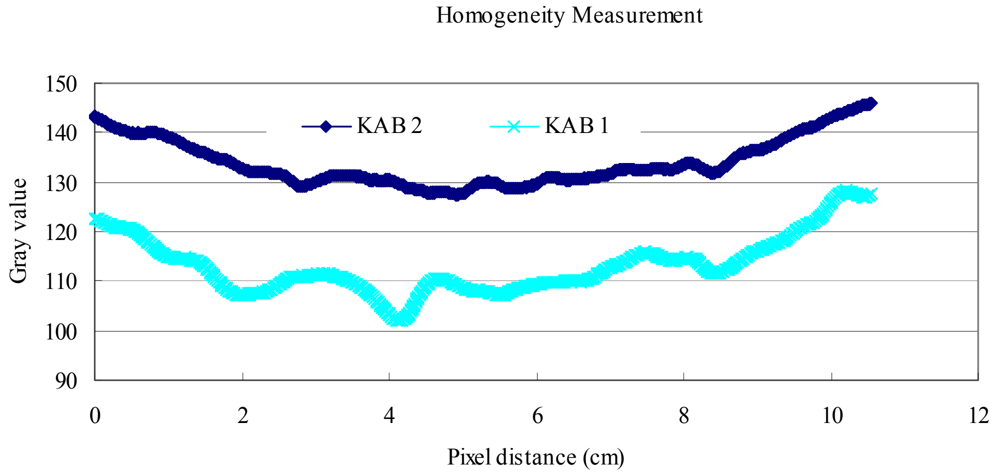

Figure 4. Gray value vs. pixel distance curve.

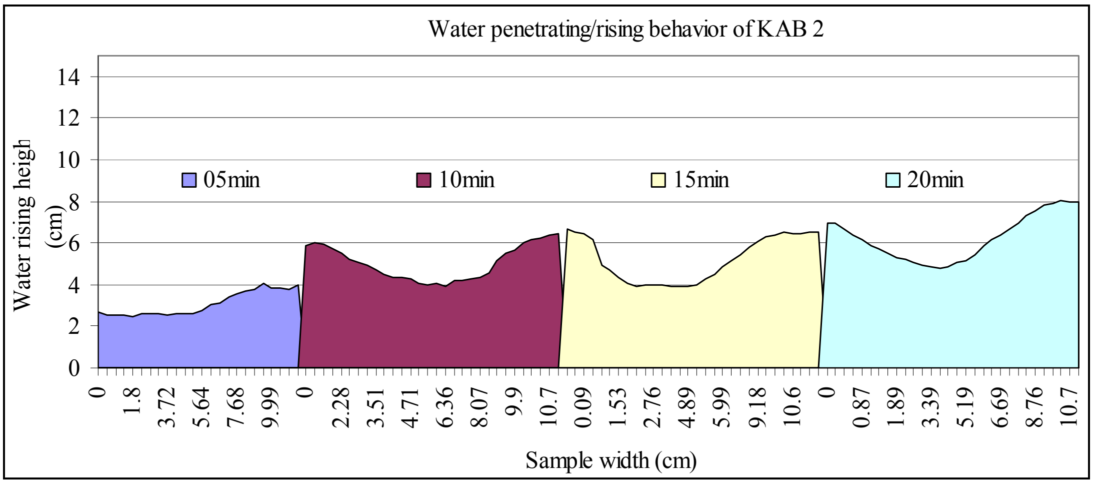

Figure 5. Water penetrating height at different immersion time for KAB 2.

Water penetrating height through the middle zone for KAB1 sample at 5, 10, 15 and 20 minute is 5 cm, 8.1 cm, 8.4 cm and 10.6 cm (**Figure 6**), respectively. In that case the water rising through the two edges and the middle is almost same for individual immersion case. The relation of incremental intrusion area which is indicated in the **Figures 2** and **3** of neutron radiographic images of the KAB samples at different immersion time is directly related to the IRA.

5.3. Determination of Incremental Intrusion Zone and Black/Gray Area

In the **Figures 2** and **3** is indicating the incremental intrusion zone *i.e.*, water is entering into a zone/place without encroachment and also shows the blue straight line. This blue line separates the actual immersion zone and the incremental intrusion zone of the immersed samples. Lower zone of the blue line is the actual immersion zone and the upper zone indicates the incremental immersion zone of the immersed samples. After irradiation of the test (wet) samples KAB 1 & KAB 2, obtained the radiographic images of the wet samples by following the procedure (f) cited in the experimental part on neutron radiographic/Agfa structurix D4DW film as a latent image using neutron radiography method. For visualize this image it is transferred to the PC using high resolution camera and is viewed in the computer screen by the image analysis software Image J. With the help of this software, the total pixel distance corresponds to the total breath/length/height of the sample is calculated along x/y-axis. From that measurement, the number of pixels/cm breath or length or height of the sample is found. In the present investigation, the actual water length in a pan is 2 cm. So, by subtracting the actual water absorption zone (height, 2 cm) from the total water absorption zone of the immersed sample, incremental intrusion zone is found. This subtraction is done by the image analysis software. But, black area and gray area can clearly be

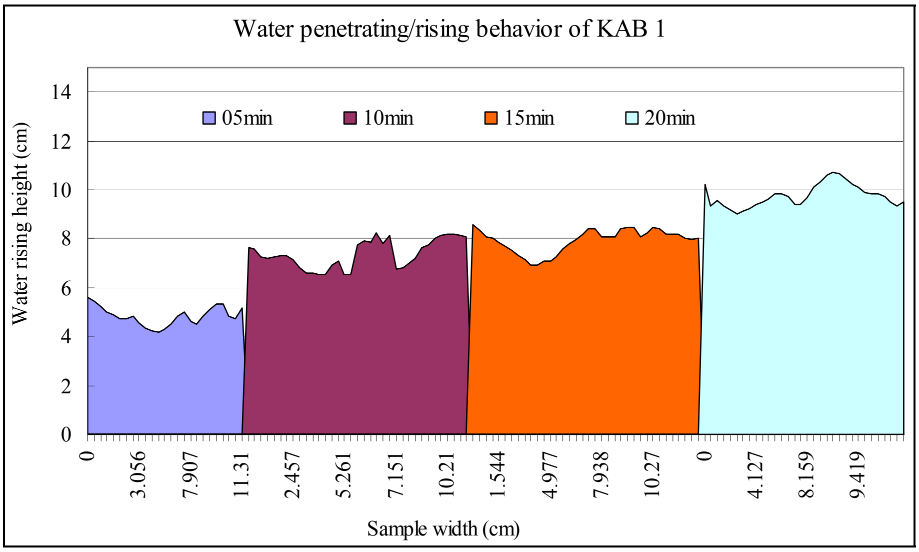

Figure 6. Water penetrating height at different immersion time for KAB 1.

distinguished only by taking radiographic images of the test sample with the help of neutron radiography (NR) method and the image analysis software. Because, Neutron radiography is a process of making a picture of the internal details of an object by the selective absorption of a neutron beam by the object and is a very efficient tool to enhance investigations in the field of non-destructive testing (NDT) as well as in many fundamental research applications. On the other hand, it is suitable for a number of tasks and impossible for conventional X-ray radiography. The advantage of neutrons compared to X-rays is the ability to image light elements (*i.e.* with low atomic numbers) such as hydrogen, water, carbon etc and can be distinguished gray area/black area of the radiographic image of the sample taken by the neutron radiography method.

5.4. Water Penetrating Behavior

Weng *et al*. studied that water absorption decreased significantly when the temperature increased due to the formation of the amorphous phase at high firing temperature. During the manufacturing time if the clay mixture absorbs more water, brick exhibits a larger pore size, resulting in a lower density. Depending on the H_2O absorption time of brick, observe differences in capillary absorption [36]. From the present investigation it also shows that the water rising/penetrating behavior through the different brick samples is like as stair, capillary, wave, zigzag shape. The resulting shape of the penetrating water into the different brick sample is shown in **Figures 5** and **6**.

5.5. Initial Rapid Absorption (IRA)

It is the measurement of the absorption rate that water is absorbed by a porous solid. It is related to the durability, porosity, pore size distribution and water absorption. It is sometimes called rising damp. The quantity, sizes and connection of pores influence the absorption rate of the brick. The IRA is reported in units of g/(30 in^2·min) [37]. In the present case, IRA is measured in units of gm/cm^3/min. Robinson [37] described three stages of capillary absorption. IRA stage is one of them. The results of IRA measurement are shown in **Figure 7**.

In the case of KAB 2, the initial rapid absorption of water is less and for KAB 1 it is higher than KAB 2. At a glance the IRA for KAB brick sample can be written as KAB 2 < KAB 1. Low values of water absorption obtained in this study indicate that the clay bricks produced were poorly porous. Internal structure of the brick is expected to be intensive enough to avoid intrusion of water [36].

Dr. Robinson [37] found a relationship between capillarity and freeze thaw durability. He stated that durability is a function of the pore structure and the nature of the fired bond. On the other hand, capillary absorption measures how well water moves through the brick, then it must have some bearing on the efflorescence potential. Theoretically, the rate of capillary absorption influences the bond between brick and mortar (mixture of lime, water and sand). York dale did not believe that there was a direct relationship between IRA and performance and did not feel that IRA should be included in ASTM specifications. This disagreement is probably related to the lack of information contained in the IRA measurement. Workmanship plays such a large role in the quality of masonry that it is hard to definitively identify the influence of other factors. Rising damp and moisture transfer through masonry. For a particular type of brick which suggests

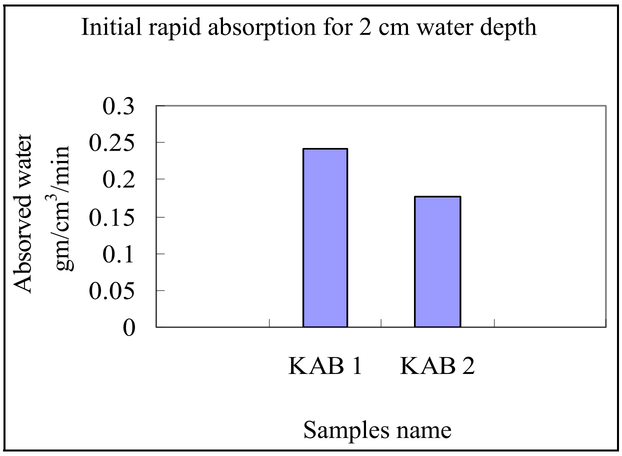

Figure 7. IRA measurement for KAB samples.

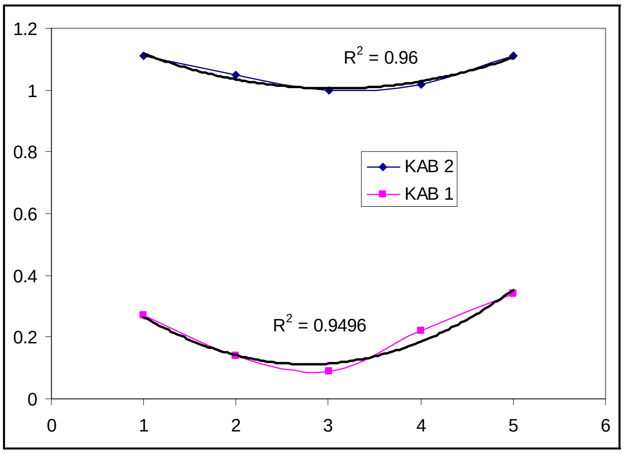

Figure 8. Optical densitometric measurement of different NR images.

that the connectivity and orientation of pores also play a large part in the movement of water in the pores [37].

6. Conclusions

The quality of a brick depends on the proper distribution of the contents/homogeneity, porosity, water penetrating behavior etc. in the sample. From the optical density measurement (**Figure 8**), it is observed that the optical density curve for KAB 2 sample is almost straight and for KAB 1, it shows far from straight line. From the points of optical density measurement, porosity, homogeneity, IRA and water penetrating behavior of view, it is pointed out that KAB is in good quality. The specific relationship between the shades of gray or density and exposure depends on the characteristics of the film emulsion and the processing conditions.

This absorption rate for KAB 2 is lower than that of KAB 1 and the water absorption increases with time gradually. **Figure 9** shows the water absorption characteristics of the samples. This indicates that after 5 minutes' immersion the absorption rate is very slow and becomes steady during long immersion time. In the case of KAB sample, steady time is higher. With higher steady time, slow absorption rate indicates the good quality. Many authors [38,39] studied that this absorption depends on submersion time, firing temperature and firing time. Few authors [40] investigate that when the mixture absorbs more water, brick exhibits a larger pore size, resulting in a lighter density.

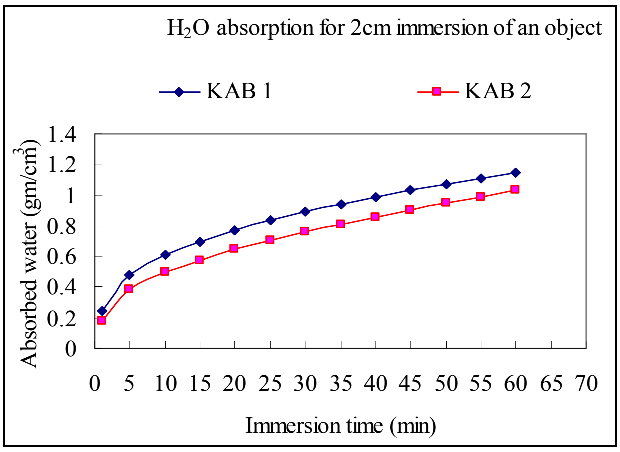

Figure 9. Water absorption rate of the sample (samples are immersed in water only 2 cm).

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The Integrated 3D As-Built Representation of Underground MRT Construction Sites

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ABSTRACT

This study facilitates the scalability of as-built data from an earlier street level to underground transportation sites from the life-cycle perspective of urban information maintenance. As-built 3D scans of a 6 km street were made at different time periods, and of 3 underground Mass Rapid Transit (MRT) stations under construction in Taipei. A scanned point cloud was used to create a Building Information Modeling (BIM) Level of Development (LOD) 500 as-built point cloud model, with which topographic utility data were integrated and the model quality was investigated. The complex underground models of the transportation stations are proofed to be in correct relative locations to the street entrances on ground level. In the future the 3D relationship around the station will facilitate new designs or excavations in the neighborhood urban environment.

Keywords: Point Cloud; 3D Scans; As-Built Model; Building Information Modeling (BIM); Level of Development (LOD); Mass Rapid Transit (MRT)

1. Introduction

Transportation systems are an important indicator of urban development. The systems are subject to consistent monitoring from a life-cycle point of view, and a process being able to reflect actual construction conditions is needed. To ensure an appropriate construction simulation, the preconstruction preparation includes programming, scheduleing, methods, emergency procedures, etc. While data are created in different stages, 4D simulation is a powerful tool for the evaluation of construction processes [1], in which both data and the construction process can be visualized, allowing the communication of this information between different parties. Nevertheless, the simulation has limitations in terms of defining actual occurrences at a site when a very complicated collection of activities and objects is presented. The complexity adds difficulties and uncertainties in creating corresponding digital representations of the data.

Point cloud models are as-built data, whose integration with old environmental data leads to a specific application in showing most current status of environment or in contrasting the changes. The model can also be presented in virtual world, in which virtual 3D city models are becoming more widely implemented by governments and city planning services, of which highly detailed 3D models that reflect the complexity of city objects and the interrelations are required [2,3]. Nowadays, city modeling has reached a new level of reality in which 3D point cloud models are created with rich geometric properties and rich details, which enable the clouds to integrate other city model types [4].

The concept of rich geometric data should be extended to new underground construction site by being capable of integrating with existing models at street level for update purposes. However, technical, policy, and institutional barriers are usually faced in integrating data from multiple state-based sources [5]. Same situation can occur to departments of a local government for spatial-referenced multiple land information databases. The data from all platforms need to be exchangeable for the best efficiency [6]. Based on shared data, system integration can be achieved to support of planning decision-making and facility management after construction. The concept of cross-sourcing virtual cities [7] should be promoted further to as-built data in a city scale, as to reflect the real content of an environment. In addition, 2D registration processes should be extended to cover 3D property registration [8], like the integration of topographic map and as-built 3D city models.

Monitoring the development of city infrastructure is an important task. Geospatial technique is used to monitor city infrastructure networks by, for example, mobile laser scanning [9]. The issues to be taken care of include the representation, identification, and segmentation of 3D urban objects. Although CityGML is a common information model for the representation of 3D urban objects, such as buildings, traffic infrastructure, water bodies [10], the presence of these subjects needs to be verified by as-built model prior to evaluation or simulation. Although high-complexity point clouds have been collected from airborne terrestrial LiDAR 3D for city modeling [11,12] with greater efficiency, underground site needs to scan and to register clouds from inside the basements or tunnels by regions.

Technologies for mapping the underworld (MTU) have been applied to the condition assessment of underground utilities of buried infrastructure [13]. Although the scans could not be made during the occurrence of water, natural gas, electricity, telecommunications and sewerage. The underground scan not only presents the relationship with outside world, but also comes with specific scan-related data application, like rock engineering [14]. With semi-underground openings available, the connection between inside and exterior can be well-established with long-term measurements [15].

Increasing need has been shown in generating real world facilities in virtual environment, involving different levels of balance between human and computer effort [16]. With the balance in mind, after the environmental data are retrieved, the human effort is still needed especially in identifying the difference between heterogeneous representations among objects by initializing planar or cylinder shapes into walls, floors, ceilings, and pipes.

1.1. Research Scope

This study combines two types of as-built records, existing street facades and new underground construction, to extend the scope of present data and to set up a checkpoint for future data comparison. As-built records, which are used to monitor the quality of transportation systems, are usually difficult to create seamlessly between different phases, such as programming, design, simulation, construction, maintenance, and afterward. In order to determine the differences via comparison, new scanned data are registered with existing ones to define their interrelationships.

This independent scan project retrieved new Level of Development (LOD) 500 as-built models of underground MRT stations without LOD 100-400 data provided. The underground data are integrated into the as-built building point cloud models above ground level to extend existing LOD 500 data for future designs and excavations nearby. In order to facilitate greater integration with other disciplines [17], this is also considered as data collaboration from heterogeneous departments toward a finalized Building Information Modeling (BIM) model.

An LOD 500 at urban scale should be conducted prior to construction in order to facilitate any new design-related activity occurring in a neighborhood area with a broader evaluation perspective. Most urban scans are visualization-oriented, despite the result actually being a collection of single buildings at LOD 500 level. Since design and nearby environment are mutually influenced, the LOD 500 of nearby buildings should be required for an overall evaluation [18]. The related data are the configuration which contributes to the proportion, skyline, or orientation of the entire region. The most straightforward way to collect data is to scan and to examine the configuration based on as-built shape.

1.2. Methodology

This study recursively creates as-built representation for future reference. The as-built representation comes with different approaches, such as from modification from former design models based on field measurements. However, the complexity of building environment usually excludes the possibility of thorough data retrieval. Additionally, the accuracy check can be difficult for cross-referenced urban environment. In contrast to correcting building data from different departments, it's more important to verify individual data set and to create cross-reference among the sets.

2. MRT Stations and Scans

The East-West MRT line of Taipei, Taiwan, is separated into 7 sectors with different construction contractors and progress (**Figure 1**). Most of the excavation has been made underground, with connections to ground level through openings for the access of machinery, materials, or workers. The openings are usually located in the middle of streets carrying heavy traffic, and are fenced off with different arrangements of materials on the ground level.

Two scan sessions, one above ground level and one underground, were conducted at two different time periods. The former has registration points set up, and can be seen without visual interference. The latter has very limited area for registration. The combination shows the scalability of as-built data from an earlier and smaller

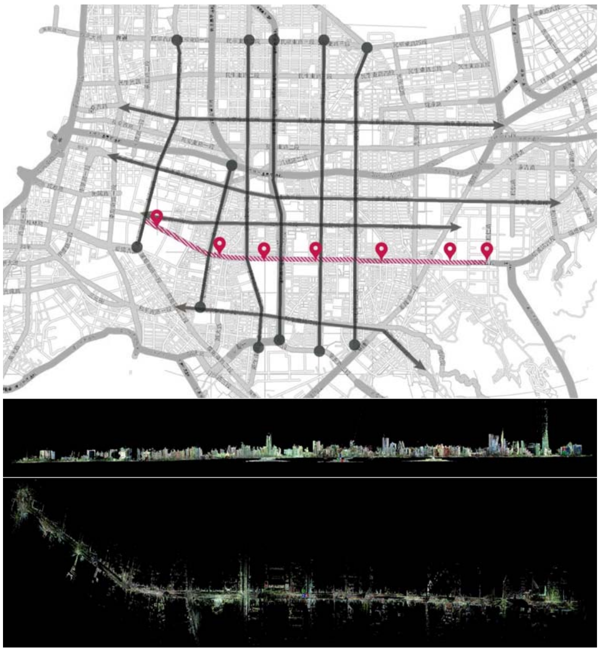

Figure 1. The newest East-West MRT line of Taipei and the point cloud model of the street.

amount of data to a broader life-cycle perspective of data. The scans were made by a Leica HDS 3000^{TM} long-range laser scanner, which applies time-of-flight technology to calculate distance.

In total, scans were made at 59 locations (ScanWorld) with 1344 individual scans of different sizes. The entire scans took 21 days (not including preliminary visits, site meetings, planning), in which 37 ScanWorlds were deployed above ground and 22 ScanWorlds were made underground. A ScanWorld is the internal data representation of the scan database for locations: a ScanWorld may consist of many scans. The 1344 detail scans were made for registrations. In this study, a ScanWorld is usually made of a large area scan (up to 360 × 270 degrees) and a number of high resolution scans of features points as detail scans. With the point spacing of 10 - 20 cm at 100 m, it usually took about one hour for each ScanWorld and another half an hour for detail scans. The detail scans are important to the precision of final scan model and the following scan jobs, because it can create a correct of 3D spatial frame for future reference. The registration tolerance is about 8 - 12 mm/100 m.

In order to avoid any obstruction to a scan, the ground level was scanned from the roofs of nearby offices and apartments. The scan locations must be chosen in such a way as to avoid, or to cover, the blind spots near the bottom of the scanner. With a scan range of 250 meters, raising height actually broadens the covered ground area. The project chose scan locations at about every 100 - 150 meters. The scan process (**Figure 2**) is made of existing scans, new ground level scans, and the addition of underground MRT scans, by referring to ground level scans.

The scan job is also divided into two parts: field scan and laboratory modeling. The former would need 3 - 4 persons for machine transportation, setup, and operation, the latter need only 2 - 3 persons for registration, data abstraction, modeling (point model, polygon model, rapid prototyping or RP model), and urban analysis (*i.e.* façade proportion, regional landscape).

After the excavation was completed, temporary covers were installed above the original street at the same location to store construction materials and fence panels. The locations and related point cloud can be seen in **Figure 3**. Each orange thin line represents the width of the point

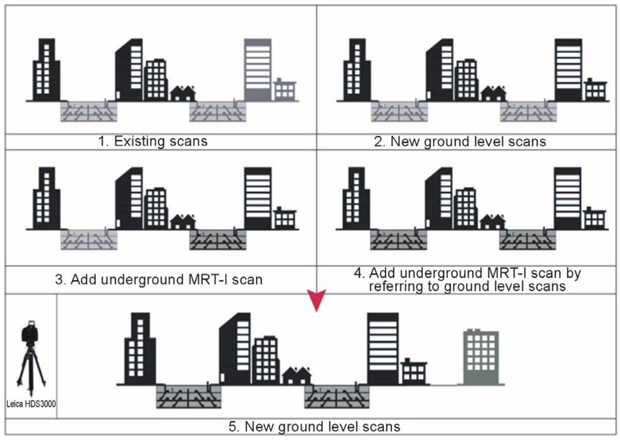

Figure 2. The scan sequence and references.

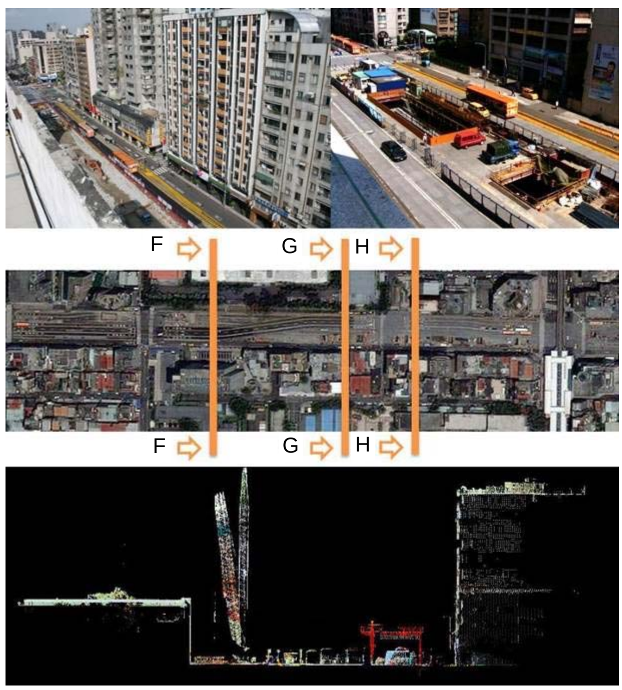

Figure 3. General construction scenes on ground level and the point cloud section at specific location G.

cloud that the section is made of, and the arrows indicate the viewing direction. The steel supports have not been completed, and the excavation, construction materials, and small machinery were placed on the ground level. Part of the construction under ground level was uncovsered during this scan period.

Shin-I street is part of the main circulation system running East-West in Taipei. The MRT construction on street level and below has a significant impact on public transportation. The reduction of the original street width for excavation and temporary working decks intensifies traffic problems. To quantify the influence, the section at each interval is extracted to illustrate the percentage of construction over the entire street width for about 10% - 40%. Street profiles can vary according to buildings on both sides, and by construction-related activities. Large construction machinery, about two-stories high, is usually installed next to ground openings close to the middle of the street, dividing the space in half. The section profiles, which can also be seen in the point cloud (**Figure 3**), illustrate the narrow clearance between the machines and the facades.

2.1. Underground Construction of MRT Stations

The MRT stations and rails are constructed beneath one of the main streets in Taipei. Although this concealed infrastructure is connected to the daily activity above, the relative locations of the two are very important, as the complexity may affect future construction or renovations. Considering the types of complexity three-dimensionally, three MRT stations were studied as 1) Type A: a joint design and development with a park at ground level; 2) Type B: shared structure with the existing MRT station; and 3) Type C: a typical underground station. Types A and B are exemplified in the following sections.

Scans (Type A) were made at different locations, such as entrances, the ticket lobby and the platform (**Figure 4**). The scanned components included: structures, rails, tunnels, materials, and HVAC systems. Additional scans were made to combine the cloud models above ground level.

Retrieving sections at different locations of a cloud model helps in the comprehension of the construction process and the inter-relationships among components. The co-related component arrangement is more likely to uncover any missing interface between systems. The sections are directly made from the as-built cloud models; they are more likely to precisely react to construction errors. The cloud-derived plan (**Figure 5**) illustrates the locations of walls, columns, staircases and temporary storage areas. The platform can also be identified on the B2 level. The cross-section of the entire station shows the relative location of the steel structures of two floor levels and the temporary working platforms.

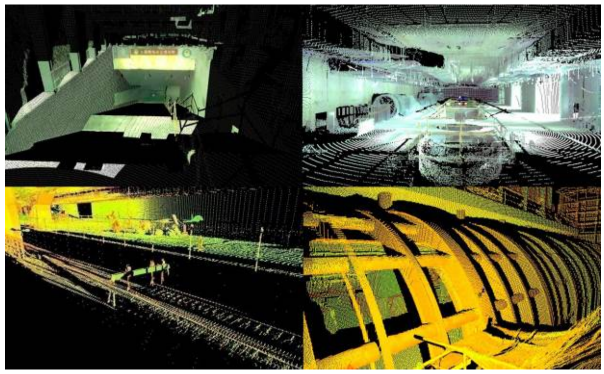

Figure 4. Point clouds of entrance, platform, rails and steel structure.

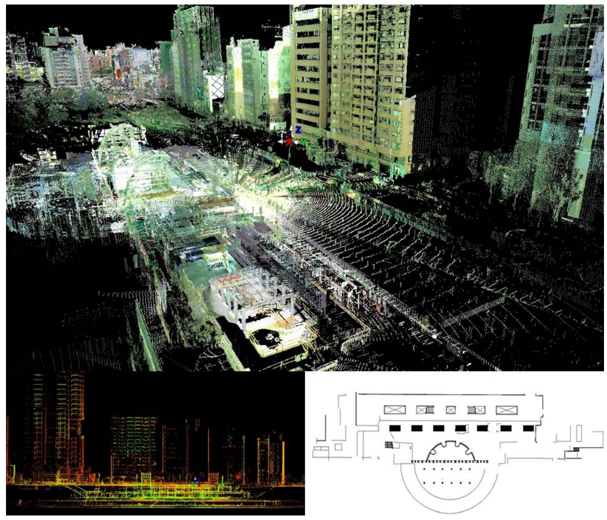

Figure 5. The point cloud of the urban environment at ground level and MRT underground (Type A).

2.2. A Top-Down Hierarchy of Cloud Models

A construction schedule consists of multiple concurrent or sequential activities. To record the entire perspective of the as-built 4D progress, the activities in terms of components have to be defined from, for example, temporary structures, excavation, foundation, steel bars, concrete, rails, and steel structure, to interior finishing. The complexity in terms of details is traditionally defined in a bottom-up structure in which each type has to relate its presence in regard to the entire perspective. To simulate the structure in this way would require tremendous effort. In contrast, a top-down viewpoint in defining complex construction activities uses the cloud model as the central database and subdivides each construction as needed at each schedule checkpoint for inspection. From the design point of view, a building is the product of a top-down process. Thus, a building cloud model is defined from a construction record point of view, which is useful because of its similar top-down nature. Most importantly, the cloud model is a feasible means of recovering the geometric construction conditions at a certain level, compared to the limited perspective of photographs, videos, 2D drawings, or 3D design models, in which the data segmentation characteristics can hardly be related to each other; the as-built database possibly would not even exist unless scans are made.

The point cloud can be navigated by users trained to read this specific type of data representation, and a project leader can also request the cloud be rotated, panned, or scaled, as needed, to look for a specific point as a vertex or a set of linear points as an edge for measurements.

3. Inspection of the Relationship between the MRT Station and the Urban Environment

The as-built facades and cross-sections of a street are very difficult to create. Government infrastructure surveys refer to traditional field data. With private property buildings, the data of an entire street or block are not only difficult to integrate as a whole, but access to the data of each private building is usually restricted. Current 2D drawings have limited block-wise information in both vertical and horizontal dimensions, especially when dealing with all street-facing buildings. Due to a lack of updated information on new and old buildings, as-built data become the only source of information for any new construction project.

3D scans of an entire block and street enable the creation of as-built data, which integrate not only various private buildings, but also the co-relationship between government and private sources of data. The integrated and co-related data enable the generation of various types of drawings [19], which eliminates the needs to visit a large number of parties, to handle the integration of sources, and to verify the tolerance of measurements. The integrated data are presented with colors that create a more effective visualization of a larger area with a scan precision of up to 4 mm/50 m (Leica HDS 3000™). An end user not only has a larger perspective of a certain region, but also the ability to use the data by simply requesting a part of the point cloud at a specific location, and the traditional sections or elevations can be created with consistency.

The Type B MRT station is located in a transportation building shared by two lines: one above ground, which was built earlier, and another underground, which was under construction. The grey part of the point cloud model was created before 2010.7.15 above ground level, and the color part of the underground model was created before 2011.3.24 (**Figure 6**). With a comparison of the section with/out the new construction (**Figure 7**), the station and its entrances can be correlated to the existing urban environment outside the station. The vertical layout of the basement levels, corridors and exits can also be seen, with their alignment to the building entrances on the ground level.

Streets, buildings, and landscape above ground level can be seen and retrieved from 2D drawings and photographs. However, the relationship between the urban environment on the ground level and the underground MRT station is not easily discernible. In order to address this problem, a cloud model, which combines data from the ground level and above, can be oriented to fulfill inspection needs. For example, the relative location between the projection of the station and the North section of the street is shown in **Figure 6**; it can be seen that the station is located right below the street, and the distance between the station and the street buildings can be determined. The cloud-derived section is used to precisely measure the building heights and the depth of the station. The 3D relationships around the station will be used to accommodate new designs and nearby excavation.

4. Point Cloud for BIM

BIM consists of 3D models, and is used for qualitative and quantitative estimation. Each building object is defined as an element, and is subject to a LOD [20]. Both the BIM and point cloud models (PCM) inherit the

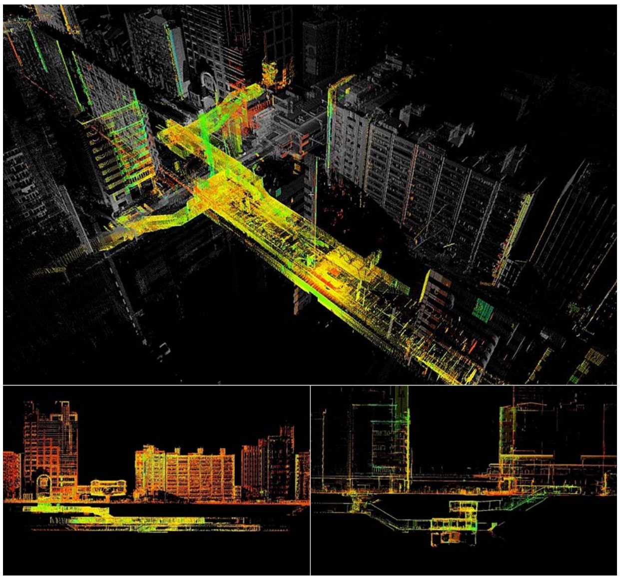

Figure 6. The point cloud of an MRT underground station (Type B) with the connections to ground level, the existing urban environment on the ground level are shown in gray color.

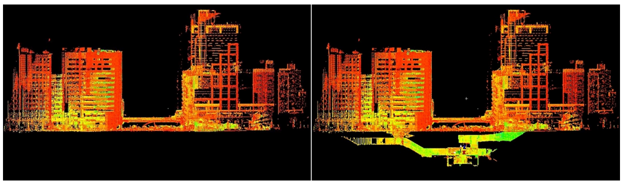

Figure 7. MRT with/out the new construction.

chronological nature of time, in which the former presents a forward design process, while the latter presents a reversed construction checking procedure, *i.e*. as the real physical objects are constructed, the scanned shape which presents as-built data is used to modify or check the LOD 300/400 for the final LOD 500 model.

BIM with object attributes can record detailed information for each building component. Although a programming language (like AutoLisp) can set definitions for vector drawing data, a user would need programming experience, skills possessed by a small number of designers or draftspersons. As with the component-based BIM, this study emphasizes an urban environment which is made of individual buildings as components.

The definition of 500 data should specify its nature in terms of execution process and the final result, and address the 4D characteristics [21] in an as-built manner. Although design and construction have been successfully defined or conducted a virtual environment, the design model has to be confirmed with as-built model. The LOD 500 usually comes after the final construction stages when most of the components are sealed or covered by finishes, and the confirmation of dimensions or shapes is usually prevented. In order to carry out 500 data, the 3D scans should be performed on as-built parts throughout the construction process [22] and monitor as-built data in terms of dimensions, configuration and adjacency [23].

This study creates a point-cloud-based data by the following steps:

- Separate cloud by parts
- Import to Autodesk Revit™
- Create 3D models
- Export images and models

The cloud data were sliced into plans, elevations and sections to be exported for modeling collaboration. Using Leica CloudWorx™, the cloud data were imported to Revit™ (**Figure 8**). In order to increase modeling speed, the cloud data were separated by plans, elevations and sections as appropriate parts to be distributed for concurrent model making by multiple persons. The 3D cloud data were in full scale, which could be measured directly. The 3D data were also presented with 2D images as backgrounds to trace model boundaries.

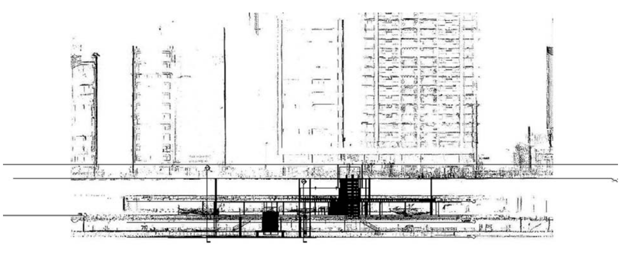

Figure 8. The type A MRT station cloud model is imported into Autodesk Revit™.

4.1. Creating 3D Models

Traditional modeling result confirms the design-oriented definition better than with construction-oriented as-built data. Complicated situations usually occur to a well-defined BIM, because quality control problems may arise in any phase of construction. A 3D as-built model can be used to verify the BIM data during construction, and to create a final 3D model after construction is completed. Cloud data clearly specify the dimensions of interiors and exteriors. Building components, such as beams, columns, walls, floors, staircases, etc., can also be identified. Scans can be applied before entities installed to inspect clearance around.

Overlaying construction (or fabrication) models and cloud models constitutes the most straightforward method of quality control in terms of checking boundaries, locations, clearances, or offsets by distances or regions. The related inspection can be viewed from all angles, and the model data can be sliced as sections at preferred intervals to avoid viewing obstructions. Most importantly, the level of construction accuracy can be justified.

The BIM for an HVAC system includes the ducts, joints, pipes and supporting accessories with specified clearances to ceiling or decks. Since the installation is based on an approved design, no intersection between components is expected in the as-built cloud models. However, the confirmation of the diameters and slopes of pipes that cross large spans, or have areas obscured by other components or partitions, are difficult to measure. If the sag of these components along linear paths is a few millimeters or inches, the deviation is usually trivial and does not show up in a BIM fabrication model. As a result, the final locations can never be determined when the tolerances differ from the designed specifications. The missing verification of the final dimensions of a component's size and location will transfer the tolerance to the following stage in facility management. Thus, the actual state of a component cannot be determined, especially when a component is sealed inside a piece of concrete wall or behind a fixed partition.

Scans were made of the MRT station before interior finishing was completed. These scans were able to record the HVAC system before it was covered by ceiling tiles (**Figure 9**). Cloud models can be used to create final drawings in the traditional way, or they can be used for confirmation with BIM. The point clouds are also used to estimate diameters. As shown in **Figure 10** (top), the cloud slice is imported into AutoCAD™. The locations and diameters of pipes are retrieved after the pipe-related points are initialized as 3D tubes. The scanned point clouds were used to create as-built polygon model at MRT lobby level (**Figure 11**).

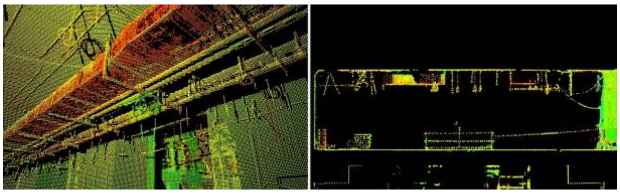

Figure 9. Section showing ducts, pipes, accessories, and partially finished ceiling.

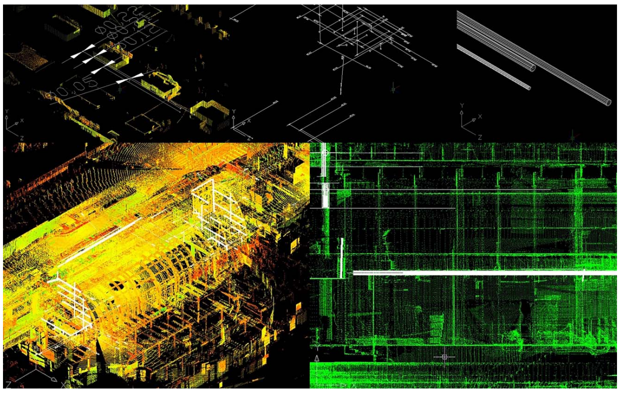

Figure 10. The floor and the retrieval of pipes (top); the arrangement and the overlapping with the cloud model (bottom).

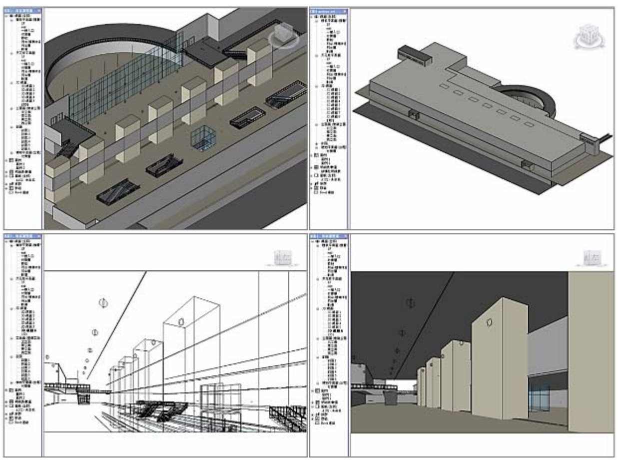

Figure 11. The polygon model for a type A MRT station based on as-built scans.

4.2. Export Images and Models

Once Autodesk Revit^{TM} has used to create the BIM data, the information can be exported as 3D models, drawings, or images, and can be used in other applications or browsing software. This study imports 3D models into Geomagic Studio Qualify™ to compare the deviation between the point cloud model and polygon model (**Figure 12**). Construction companies can confirm quality control by first scanning, and then overlapping the scans with the LOD 300/400 model for possible misalignment. Any occurrence during the construction process in which the as-built data do not align, indicates a possible problem as an offset from the original BIM representation.

The hardware burden in this project was reduced by avoiding the addition of too much information in a single file. Although BIM comes with 3D information, the model can still combine bitmap images or vector maps for the purpose of integrating building and urban data The AutoCAD^{TM}-exported MRT model (.dxf) is 19,478 KB, in contrast to the size of vector drawings of 2745 KB, with a larger area covered in a smaller size. It only requires 54.9 MB (12.3%) of RAM.

The 3D cloud model is also used to cross-reference values and to integrate information (**Figure 13**). For existing facilities, underground pipes, street lamps and fire hydrants, the construction process can be delayed unexpectedly. BIM model can integrate various maps as GIS to facilitate M&E execution.

Scan data can also meet traditional needs in architectural practice. For example, working drawings are usually created before the construction stage. The drawings specify quality control by measurements. Nevertheless, reference to after-construction structures can be difficult if barriers are obstructing the area to be measured. This problem is solved by referring to the cloud model, and by either directly measuring or using editing tools to remove the interference. The sections are similar to plans, except different projection angles can be selected immediately by slicing corresponding parts.

4.3. BIM Problem of the Building under Construction

The problems involved in directly applying point cloud data for BIM checking include the following:

- The surface model file created from the point cloud is too large to be easily manipulated. To manipulate large data set inside scan software is efficient because better imbed algorithm is provided for fast browsing and editing. An easy and straightforward way to accelerate the manipulation is to increase computer power and reduce cloud model size by boxing the needed part only for domain specific data application.
- Scan data may be insufficient or incomplete due to the viewing angles being blocked by objects. Additional scans have to be made. Scan from different angles have to be planned to recover the missing part of geometries.
- Scans only record surface details, and the internal composition of some components cannot be known. One way to know the internal composition is to scan ahead of the construction schedule, before the components being sealed.
- Finishing is incomplete during this project period, which leads to the final surface smoothness and the construction quality level being unknown. Building

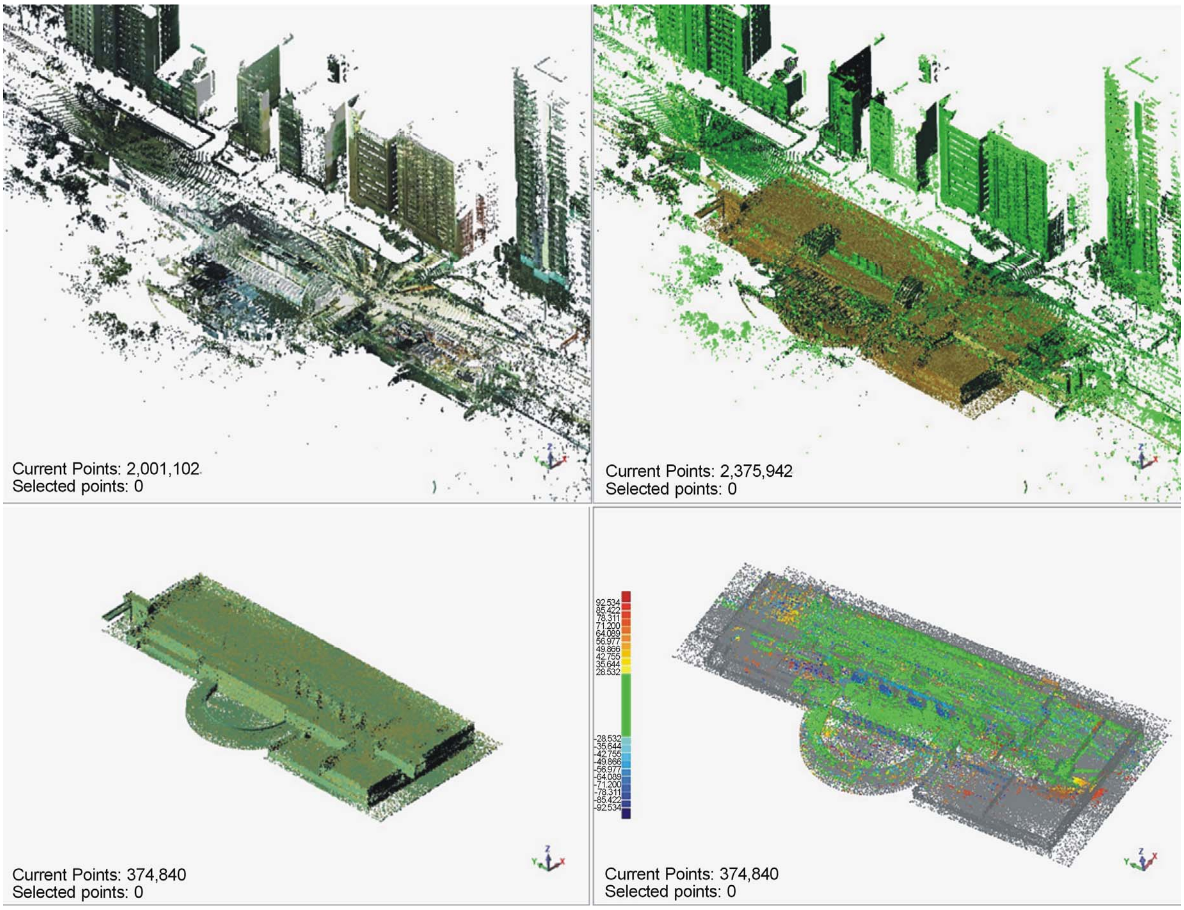

Figure 12. The combination of the cloud model (top left) and the polygon model (bottom left) into the alignment check of the main platform (bottom right).

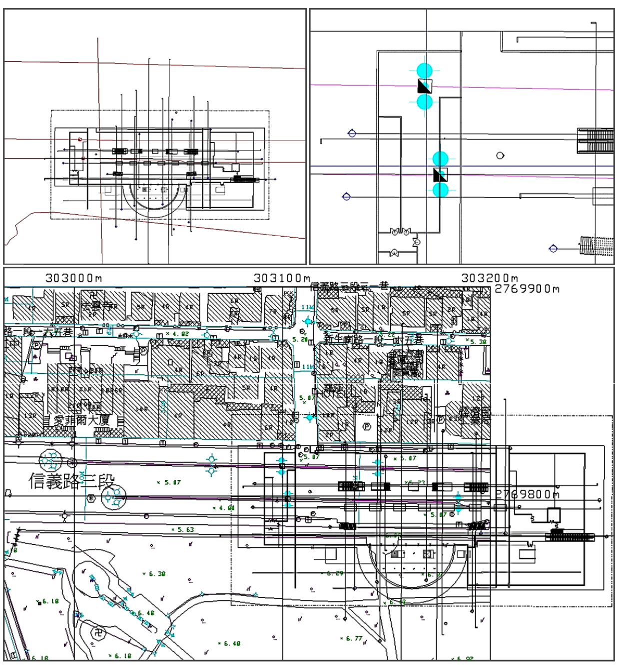

Figure 13. Overlapping BIM model with the maps of street lamps, utility boxes, pipes, and topographic information.

life cycle consists of different phases. Scans should be made accordingly for thorough records. In the future, scans need to be made again after building is occupied for a while when budget is available.

- Scans cannot be applied to transparent or reflective materials which would need other auxiliary field measurement device (total station or tape measure) for data retrieval.

5. Conclusions

This project was restricted by resources, and it was unable to produce a thorough life-cycle record of all stages. Although this MRT line was in the final stages of construction and is running just before the end of 2013, a future study could include issues based on the data created in this project and data integration pattern for new constructions. Chronological scans should be conducted after interior finishing and at least one year after the start of operation for post-occupation response. As stated in the methodology, the recursively defined as-built representation and related framework will contribute to future nearby construction works, and lead to a better start in

BIM since this project.

In order to combine the cloud model and original BIM in the design stage, this project was conducted as a local pioneer study, without any access to the internal MRT data, which was withheld for security reasons. Although no evaluation with the existing model was made, the project did create drawings and share the cloud model with the MRT administration. As a result, the project was conducted as an independent source, which is feasible for quality and schedule control.

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