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A methodology for quantifying adaptability of buildings using an analytic hierarchy process

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ABSTRACT: While adaptable building design is an area of increasing interest, there is a dearth of published empirical evidence regarding which physical characteristics of buildings are most effective at facilitating adaptation. This paper outlines a methodology for identifying physical characteristics that facilitate or impede adaptability; the methodology uses expert elicitation (survey) to empirically measure the "adaptability" of different buildings. The survey asks about hypothetical adaptations to buildings on the Clemson University campus. Participants are presented with a series of pairwise comparisons of buildings and asked to rate the relative attractiveness of the buildings for the hypothetical adaptation projects. They are also asked to compare the buildings based on the relative presence of general adaptability strategies (such as *long life* and *loose fit*) in their designs. Four case study buildings, resulting in six pairwise comparisons, are utilized. In this manner, expert evaluations are grounded in real-life buildings with the intention of producing meaningful results. An analytic hierarchy process (AHP) is used to formulate the survey, process the data, and determine quantitative rankings of adaptability. Results of the study (forthcoming) will be used to confirm the efficacy of design strategies recommended by other authors, and to provide quantitative comparisons on the effectiveness of these strategies on adaptability.

KEYWORDS: adaptability, flexibility, AHP, resilience, expert elicitation

INTRODUCTION

"A building is not something you finish. A building is something you start." This pithy line from Stuart Brand sums up the thesis of his seminal work on building adaptability, *How Buildings Learn* (Brand 1995). As technology, politics, business, and user demands are changing ever more rapidly, it is becoming more and more apparent that for our buildings to remain relevant they must be able to adapt to new circumstances. In recent years, organizations and researchers have developed design-for-adaptability (DfA) guides that present strategies for making new building designs more adaptable (Schmidt and Austin 2016; Kestner et al. 2010). However, there is a lack of empirical data demonstrating how effectively these strategies create more adaptable buildings. What's more, a consistent theme in recent technical literature on the topic has been the need for methods to measure the adaptability in new designs (Rockow et al. 2018; Heidrich et al. 2017). The current paper presents a new methodology for ranking adaptable designs and ranking the relative effectiveness of different DfA strategies. The methodology uses expert elicitation and an analytic hierarchy process (AHP) and is a jumping-off point for future quantification of adaptability in buildings.

As research in sustainable building design has increased and matured, the issue of embodied energy has emerged as a primary consideration. Buildings are often demolished well before the end of their physical lifespans, leading to waste of embodied energy (O'Connor 2004). This end-of-life waste can even outweigh lifetime energy savings produced by efficient systems and design (Wilkinson and Langston 2014). Therefore, sustainable building designs must consider not only the immediate future of the building, but the eventuality of the building becoming obsolete. Fig. 1 shows the life cycle of a typical building (Rockow et al. 2018). As the building ages, it eventually ceases to meet user needs and is either demolished or adapted. This study focuses on the "Initial Design" stage of the life cycle; the objective is to quantify the impact of initial design decisions on future adaptability. In other words, can design features included at the outset lead to an increased likelihood of later adaptation? If so, which ones, and to what extent? To address these questions, the proposed methodology has been developed to exclude contextual (e.g. social, political, historical) factors and focuses solely on design features. Though physical features are not always what precipitate the decision to adapt or demolish a building, they are the only aspect of the building that can be influenced by the designers. Other studies have performed surveys and developed tools for measuring the adaptability in general (Geraedts 2016; Conejos et al. 2013), but this study is distinct in that it focuses solely on physical features.

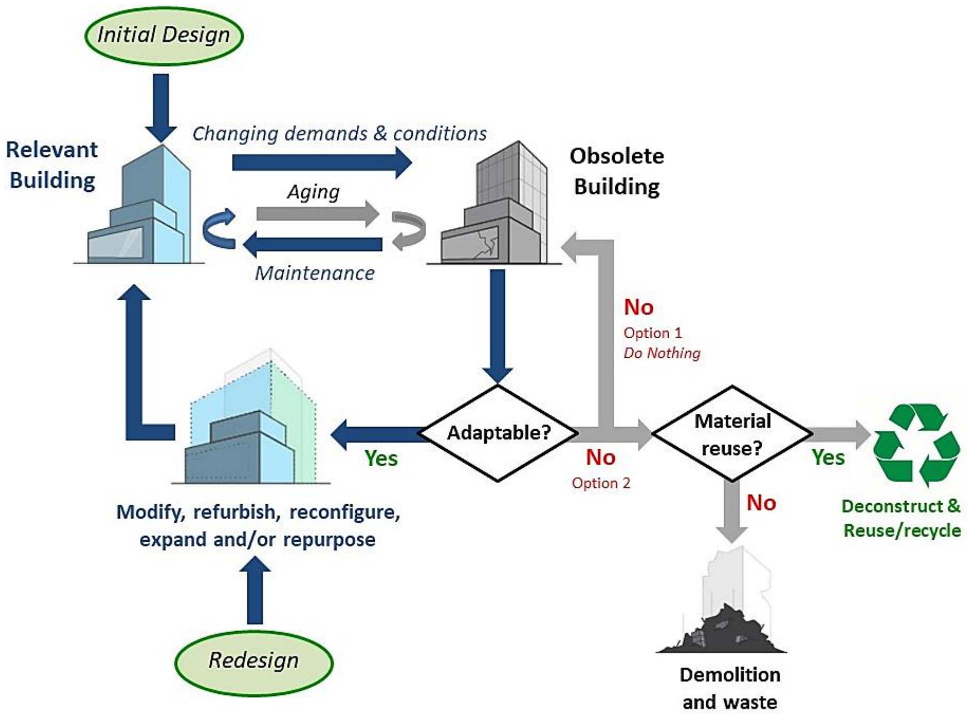

Figure 1: Building life cycle (Rockow et al. 2018).

At time of writing, the proposed methodology is being deployed. Experts are rating the importance of four dimensions of adaptable building design: *long life*, *loose fit*, *simplicity*, and *layer separation*. They are also judging the adaptability of case study buildings through pairwise comparisons. These responses will be aggregated to "score" the adaptability of different buildings. This paper describes the methodology being used to obtain these scores.

1.0. BACKGROUND

1.1. Definition of terms used in the current paper

Definitions must be clarified for *adaptability* and *adaptation*. According to Dolnick and Davidson, a building *adaptation* is a rehabilitation or renovation of an existing building or structure for any uses other than the present ones (1999). *Adaptability* is the ease with which buildings can be physically modified, deconstructed, refurbished, reconfigured, or repurposed (Ross et al. 2016). In this paper, an *adaptation* is a significant change to a building's space plan, envelope, services, or structure, beyond an aesthetic update or rearrangement of furnishings. Specifically, this paper focuses on *design-based* adaptability, which refers to that adaptability that is due to the physical design of the building. Contextual features such as market demand, social issues, and historical status are not a part of design-based adaptability. According to Ross et al. (2016), design-based strategies are "aspects of a design that can be manipulated to increase the potential for adaptability". There are numerous physical characteristics that can influence adaptability. For this study these characteristics have been condensed into four general dimensions: *long life*, *loose fit*, *simplicity*, and *layer separation*. These dimensions are defined below and are included in the instructions given to experts participating in the study.

- *Long life*: The usable lifetime of a building can be extended through overdesigning the structure, using durable and high-quality materials, and through designs that slow the physical aging of a building (Ross 2017).
- *Loose fit* refers to openness in the floor plan and building section, and the ability of space to perform multiple functions with minimal adaptation (Council on Open Building 2018).
- In individual systems and buildings as wholes, *simplicity* indicates the use of regular, repetitive, easily understood parts or spaces with minimized unique conditions (Ross 2017).
- *Layer separation* is the physical and functional separation of building layers (i.e. space plan, envelope, structure, services) such that one can be modified or removed with minimized effect on other layers (Brand 1995).

1.2. Previous work in quantifying the adaptability of buildings

As previously mentioned, quantifying the adaptability of buildings has been an area of increasing interest to many researchers. A few of the most relevant works are reviewed here. A more comprehensive review of methods for modeling and measuring adaptability can be found in Rockow et al. (2018).

Ross et. al. identified eleven design-based "enablers," or strategies, for creating adaptable building designs (2016). Experts were asked to rate these enablers according to their relative importance in determining the adaptive potential of buildings. In a later paper, Ross sorted the eleven enablers into four general adaptability dimensions: *long life*, *loose fit*, *layer separation*, and *reduce uncertainty* (2017). These dimensions were used in the Learning Buildings Framework (LBF), a tool for calculating an adaptability score based on the physical features of a building. The current paper's four dimensions are similar; however, the current paper omits *reduce uncertainty* and adds *simplicity*. A future work will compare results from the methodology in the current paper to scores from the LBF (Becker 2019).

Another rating tool, FLEX 4.0, developed by Geraedts, was designed to assess the adaptive capacity of buildings based solely on physical features, or flexibility key performance indicators (FKPIs) (2016). Geraedts identified 44 FKPIs. The tool utilizes default weighting factors for the FKPIs, or the user can alternatively assign their own weighting factors.

Based on previous work, the proposed methodology will feature four dimensions of adaptability. The dimensions chosen (*long life, loose fit, simplicity,* and *layer separation*) are broad enough that the more specific DfA strategies found in literature fall into one or more of the dimensions. Thus, any aspect of a building's physical design can be sorted into one of those dimensions. The authors chose to focus on four general dimensions rather than more specific aspects in order to make the survey manageable for participants.

1.3. AHP and previous uses in building design studies

This study will use an AHP-based survey of building design professionals. The analytic hierarchy process (AHP) is a decision-making tool that was developed by Saaty (Saaty and Alexander 1981). AHP simplifies complex decisions by decomposing them into a hierarchy of pairwise comparisons between alternatives and between criteria. The first step is to identify criteria and develop a criteria importance weighting vector through pairwise comparisons. Second, the alternatives are compared on the basis of each criterion. The results of these two steps produce a final weighting vector for the alternatives, giving the relative attractiveness of each alternative based on the presence of the criteria. AHP is commonly used for group decision-making because group members' answers can be aggregated (Saaty 2008). The proposed methodology uses AHP to calculate the building adaptability scores in two ways; these processes are explained in detail in the next section.

Though AHP has not been used previously to study building adaptability specifically, AHP has been implemented in other aspects of building design. Alwaer and Clements-Croome used AHP and expert elicitation to develop a model for rating the level of sustainability in sustainable intelligent buildings (2010). Wong and Li used an AHP and expert surveys to investigate the relative importance of selection criteria that are judged when designing intelligent building systems (2008). Bhatt and Macwan surveyed experts in India using an AHP-based questionnaire to determine which sustainability parameters were most important for buildings (2011).

The three studies described above each had experts complete an AHP-based survey and then used the results to develop importance weightings for certain parameters. This is similar to the current study's objective to use expert elicitation and AHP to develop rankings of the importance of physical factors that contribute to adaptability.

2.0. PROPOSED METHODOLOGY

In summary, critical information from four buildings was condensed into case study packets, which are reviewed by experts prior to their taking of the survey. The experts use that information to complete a 102-question survey in which they are asked to perform pairwise comparisons of the buildings (thus, performing six comparisons among four buildings). For each comparison, the experts answer twelve questions about potential adaption projects, and four questions about the presence of the four dimensions of adaptable design in each building. Finally, the experts are asked to rate the relative importance of the four dimensions. Each question is answered using a simple point-assigning system to express the level of the expert's preference for one option over the other. Once the survey data are collected, a two-part AHP will be used to calculate relative adaptability weightings for the buildings and dimensions.

2.1. Case studies

The researchers chose four buildings on Clemson University's campus for the case studies. Each case study summarized the building's physical features in a 10-15 page document. A summary table of the building features can be seen in Fig. 2. Below is listed the rationale used for selecting buildings for the study.

- All buildings were of a similar size (i.e. floor area).
- All buildings were low rise.
- All buildings were built within the last thirty years.
- Buildings had varying current uses, including: art/architecture studio building, student center, dormitory building, and office/classroom building. This was done purposefully to provide different original building designs for the experts to compare.
- Buildings have varying structural systems, footprint shapes, and envelope materials. Again, this was done purposefully so that no two buildings were too similar in their physical aspects.

Building A (Watt Family Innovation Center)

- 4 stories + basement, total 65,300 SF.
- Movable glass partitions.
- Raised plenum HVAC system.
- Special structure: reinforced concrete cast on metal deck composite with beams and column.
- Green roof.

Building B (Academic Success Center)

- 3 stories, total 40,000 SF.
- Classrooms, offices, large lecture room.
- Structure: load-bearing CMU, concrete beams and columns.
- Distributed HVAC system.

Building C (Lee Hall III)

- 1 story + mezzanine, 55,000 SF
- Open studio space, offices, classrooms.
- Skylights and light sensors.
- Geothermal well heating system.
- Green roof.

Building D (Stadium Suites)

- 4 stories, total 74,000 SF.
- Dorms, community rooms.
- Structure: load-bearing CMU, steel beams and columns.
- Distributed HVAC system.

Figure 2: Summary of case study buildings.

2.2. Survey questions

A purpose-made spreadsheet was created for survey completion by participants and for AHP analysis. The survey questions were written in accordance with questionnaire design guidelines by Brace (2008). On the participant side, the spreadsheet has seven pages; one page for rating the importance of the dimensions, and one page for each pairwise comparison between the buildings. The pairwise comparison pages are all duplicates of each other except that each page compared different pairs of buildings (A vs. B, B vs. C, etc.). The survey asks twelve "adaptation scenario" questions and four "dimension" questions per pairwise comparison (examples below). These questions are identical between the six comparisons.

Example adaptation scenario question: Which building is most suitable for conversion into office space?

Example dimension question: Relative to one another, to what extent does each building exhibit long life?
All questions, regardless of type, use the same answer format. Participants are prompted to distribute eleven points between the two given options; higher point values indicate that an option is preferred for the question at hand.

2.3. Recruiting experts

At the time of writing this paper, fifteen experts have been engaged in the study. The target is to have participation across various disciplines in the design and construction industry. The following numbers are used as approximate recruitment targets: six architects, three structural engineers, three façade engineers, three mechanical engineers, two electrical engineers, two geotechnical engineers, and three project managers, for a total of twenty-two participants.

2.4. AHP design

The analysis used in this methodology contains multiple steps, some of which are parallel. One strength of the proposed method is that it produces results that can be used to crosscheck each other. Broadly speaking, the experiment seeks to answer the question, "Which case study buildings are most adaptable?" This question is answered using two different parts and is based on aggregate responses of the experts. The explanations below go in order of the steps required in analysis, not in order of the appearance of questions in the survey tool itself. The rating vector calculation method used in this paper is recommended by Saaty and Hu (1998) for accurate results.

2.4.1. Part 1

Part 1 functions as a typical AHP. First, the expert performs pairwise comparisons between the buildings, comparing the relative presence of each dimension. Take for example the expert comparison of "long life" in buildings A and C. Building A receives 3 points and C receives 8 points, indicating that the expert believes that C exhibits significantly more "long life" than A. The expert repeats this for all building combinations, and their numerical responses populate a "building comparison matrix" (Fig. 3, left). (Note the 3/8 value at the intersection of "Bldg A" and "Bldg C," corresponding to the expert's scoring. Also note that the diagonal of the matrix is made up of 1's because there, the buildings are compared to themselves. Values on either side of the diagonal are mirrored because they represent the same comparison, only done in the opposite order, e.g. "A vs. C" and "C vs. A.") A *dimension presence vector* for each dimension is calculated via matrix math, expressing the relative presence of that dimension in each building (Fig. 3, right). In this example, building D exhibits the most "long life" with a presence rating of 0.38, which is approximately three times as much as Building B, which is rated at 0.12.

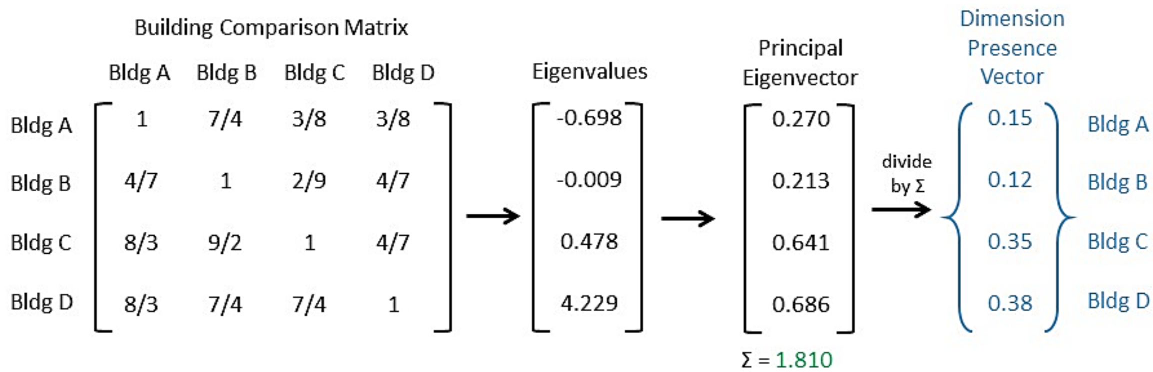

Figure 3: Calculation of dimension presence vector for "long life" (Part 1 of method).

The four *dimension presence vectors* are assembled into the *dimension presence matrix* (Fig. 4, left). Then, the expert performs pairwise comparisons between the dimensions themselves, rating the relative importance of each dimension to adaptability. For example, the expert compares "long life" to "loose fit" and gives each a score, and so on, until they have compared all four dimensions to each other. The procedure for this step is exactly like that used in Fig. 3, except dimensions are being compared, not buildings, and the result is a *dimension rating vector* (Fig. 4, center). Finally, the matrix and vector are multiplied to produce an *adaptability rating vector* (Fig. 4, right). This expresses the relative adaptability of each building. In this example, building C at 0.309 is the most adaptable. Building C is approximately twice as adaptable as building B, which has a score of 0.143. These numbers are hypothetical and are used as an example; they will be replaced by expert responses for the study.

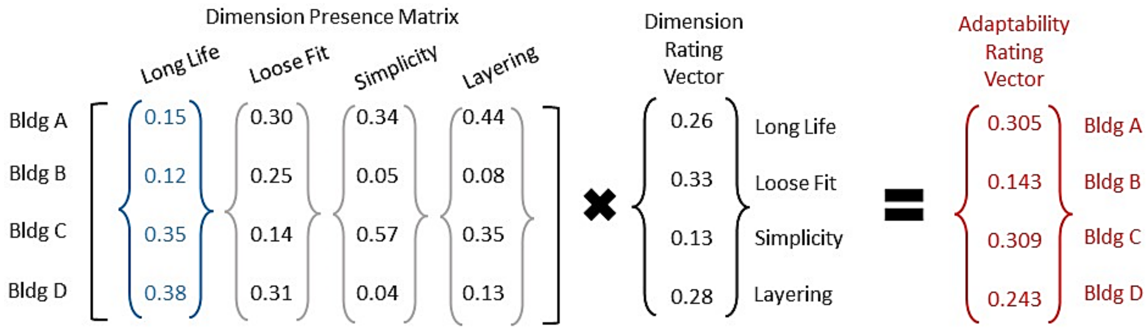

Figure 4: Calculation of adaptability rating vector (Part 1 of method).

2.4.2. Part 2

The end result of Part 2 is also an *adaptability rating vector*. However, in Part 2 adaptability is not computed based on dimension presence and importance but is generalized from a range of questions addressing hypothetical adaptation scenarios for the buildings. First, the expert performs pairwise comparisons between the buildings, like in Part 1. However, this time, the buildings are compared based on their relative attractiveness for a given adaptation scenario. For example, the expert compares all four buildings based on the question, "Which building is more suitable for conversion into office space?" The pairwise comparisons populate a *relative adaptability matrix* (Fig. 5, left), from which a *specific adaptability rating vector* is computed (Fig. 5, right), which give the relative score for each building.

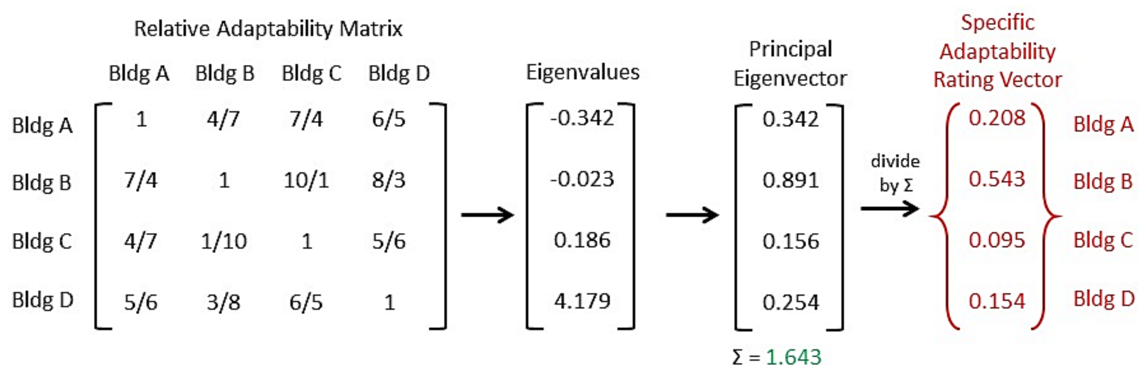

Figure 5: Calculation of specific adaptability rating vector (Part 2).

One specific adaptability rating is calculated for each scenario. In order to make the final adaptability ratings generalizable across all facets of adaptability, the expert is asked the make the same pairwise comparisons based on twelve adaptation scenarios, addressing changes to the structure, envelope, foundation, space plan, and services (Brand 1995). The twelve *specific adaptability rating vectors* are aggregated to produce a final *adaptability rating vector* that expresses the buildings' relative general adaptability, according to that expert.

Because the twelve adaptation scenarios address various aspects of building design, a given expert may not have the experience and/or expertise to answer each question with confidence. To account for this, each adaptation scenario question is followed by a request for the expert to rate their confidence in their answer, and their answers will be weighted accordingly. Also, for all calculations based on the experts' pairwise comparisons, a consistency ratio is calculated (Saaty and Alexander 1981) to check that the experts' answers within each pairwise comparison are internally consistent. If inconsistency is detected, the researchers will contact the expert to clarify their answers.

2.4.3. Comparison between results of Parts 1 and 2

For each individual expert, both parts produce an *adaptability rating vector* that, theoretically, represents the overall relative adaptability of each building. The vectors from both parts will be compared to observe whether both methods lead to similar results for the same expert. Next are listed some possible conclusions that may be drawn based on observed similarities or differences between the vectors.

If one expert's two final rating vectors have similar values: The expert's judgments about the relative importance of the four dimensions of design-based adaptability are consistent with their judgments about adaptability in real-life scenarios. This is evidence that the experimental method reliably determines which dimensions most affect the expert's decision-making.

If one expert's two final rating vectors have dissimilar values: The expert's judgments about the relative importance of the four dimensions are not consistent with their judgments about adaptability in real-life scenarios. This means that one or both of the methods may not accurately reflect the reasons behind the expert's decisions in adaptation scenarios. One possibility is that questions for Part 1 are too theoretical and do not reflect the opinions behind the expert's scenario-based responses to Part 2. Another is that the adaptation scenario questions may be too specific and, together, are too limited to reflect the full scope of possible adaptation projects.

2.4.4. Group comparisons

The analysis described earlier in the paper is completed for each expert individually. Then, following established methods, the experts' results will be aggregated (Ossadnik et al. 2016; Forman and Peniwati 1998). The data can be aggregated and compared in multiple ways; results can be compared by individual, by expert group, or can all be aggregated together. The consistency of the results can be compared within expert types and across all the experts to observe whether the methodology produces consistent results, and to judge whether it is feasible to obtain objective judgments of a building's adaptability from expert elicitation.

CONCLUSION AND NEXT STEPS

The methodology presented in this paper uses AHP to answer the question: "What physical design features lead to adaptable buildings?" The method uses expert elicitation to derive ratings for: the adaptability of building case studies, and: the relative importance of the four major dimensions of adaptable design features. At the time of writing, the survey instrument and analysis method have been developed by the researchers, and initial surveys are underway.

Once sufficient responses have been collected, the researchers will perform the AHP analysis to obtain weightings for the four case studies and the four adaptability dimensions. These weightings will be compared to adaptability scoring systems from other literature (Ross 2017; Geraedts 2016; Conejos et al. 2013). Following the US-based study, the researchers aim to expand the survey to include international professionals whereby commonalities and differences between views on adaptability can be evaluated.

ACKNOWLEDGEMENTS

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