TOWARDS A PREDICTIVE METHOD FOR BENEFITS REALISATION THROUGH MODELLING UNCERTAINTY IN FRONT END DESIGN

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Joas Serugga, Mike Kagioglou, Patricia Tzortzopoulos
University of Huddersfield U.K.
CONTENTS

- Background To Research
- Why This Research
- Drawing Context to Uncertainty in Design
- Research Methodology
- Benefits Realisation and Front End Design
- Key Concepts in Uncertainty Modelling
- The Dempster-Shafer Theory
- Conceptual Model for Uncertainty Modelling
- Looking Ahead & Conclusions
WHY THIS RESEARCH?

The Setting for this Research is in Social Housing Design Research. Social Housing Benefits stretch many stakeholder interests calling for contextual decision making.

The Delivery of Social Housing Benefits is increasingly a focus of many stakeholder interest creating varied expectations and bringing uncertainty to processes. Much of these benefits are determined during FED design processes. Yet FED decision making is Poorly Studied.
WHY THIS RESEARCH?

- Focus Usually on delivery of high-level goals such as enough social housing, within a given budget.
- Limited focus on how uncertainty is influencing design decision making processes to meet changing user use cases.
- A utilitarian perspective can focus decision making around their Utility function (UF) to harness Consistency $A_3 (Y_3, Z_1), A_2 (Y_2, Z_2), A_1 (Y_1, Z_3)$ are of Equal Utilities so have to be explored with the DM)
WHY THIS RESEARCH?

- New Analytical Approaches to uncertainty in Design Decision Making in Social Housing Need Now to be Explored using mathematical approaches.
- This Has to Be Focussed on the Front End Design Stages where changes can be quicker & Cheaper to make, yet with the Most Dynamism information exchanges.
- Drawing Context to the role of uncertainty in Design Processes can also help draw focus on utility of benefits for social housing.
**Problem 1:** Research into Complexity of FED and its relation to Dynamic Context and Value Generation is Needed

Development & Refinement of one of one or more of Solutions to date

Conceptualisation of Front End Design Adapted from Lawson (1983 p.24)
**BACKGROUND – DYNAMIC CONTEXTS**

**Problem 2:** Context Specific Constraints can bring about uncertainty in Process; BUT, Form a Great Part of Design Decision Making – and ultimately Benefits Realisation in Social Housing.
RESEARCH METHODOLOGY....

- A Mixed Methods Approach to Capture the Essential Heuristics, Subjectivity, Linguistics Adopted: Set Basis for Context
- Literature Review to Assess the Application of Probability Theory for Uncertainty and Predictive Modelling in the face of changing context studies – a basis for theoretical validation of constructs and Architectural system (Evidence Based Design – EBD, Experience Based Design - ExBD)
- Development of a Mathematical Model for Data Analysis - based on Probability Theory (Using Dempster-Shafer Theory – to model uncertainty in design decision making; and Hidden Markov Modelling to model the changing user and design requirements) – in a utilitarian perspective.
- Case study Research plus Action Research - Opportunities for Evaluation of Model through data analysis for 3 housing models in 3 different contexts.
KEY CONCEPTS IN MODELLING UNCERTAINTY

Adapted from Kukulies and Schmitt (2018)
DEMPSTER- SHAFER THEORY

• Multi Attribute Decision Making (MADM) during design such as in Social Housing involves uncertainty or use of incomplete information.
• Current tools and practice however are unable to account for this uncertainty of the effect of ‘making do’ during FED processes (Hua et al., 2008, Beynon et al., 2001)
• Bayesian theoretic of conditional probability and adaptations such as Dempster-Shafer theory (DST) are able to model uncertainty within a body of evidence (BoE) - (Dempster, 2008, Shafer, 1976, Altieri et al., 2017, Wang et al., 2016, Awasthi and Chauhan, 2011, Hua et al., 2008, Beynon, 2005).
DEMPSTER-SHAFER THEORY – CONT...

- DST allows for modelling of uncertain and unknown knowledge areas within a BoE through providing the Frame of Discernment (FOD) and a basic probability assignment (BPA) (Denœux et al. 2018, Zhou et al. 2017, Tang 2015)

  \[ \text{FOD} = \text{denoted as } \Theta = \{S_1, S_2, \ldots, S_i, \ldots, S_n\} \]

- The use of DST also helps reduce indeterminacy in decision making as argued by (Chen et al. 2018)

- In an action space, an incomplete BoE is assigned a basic probability assignments (bpa) for its describable and partially describable focal elements and the indescribable/FOD all assigned as DS mass functions \([m(.)]\) (Denœux et al., 2018).
In a BoE with \( n \) as set of focal elements in a BoE \( m(.) \) defined as \( s_1, s_2, ..., s_n \), with corresponding weights of \( b_1, b_2, ..., b_n \) respectively, according to Beynon (2005), the BoE could be represented as:

\[
m(s_i) = \frac{b_i p}{\sum_{j=1}^{d} b_j p + \sqrt{n}}, j = 1,2,...,n \text{ and } m(\emptyset) = \frac{\sqrt{n}}{\sum_{j=1}^{d} b_j p + \sqrt{n}}
\]  

Where \( p \) is the weighting for the criteria and \( \emptyset \) the FoD. The basic probability assignment (bpa) can also be represented by a belief function \( Bel (A) = \sum_{\emptyset \neq B \subseteq A} m(B) \) and a Plausibility function \( Pls (A) = \sum_{B \cap A \neq \emptyset} m(B) \). For two independent mass functions \( m_1 \) and \( m_2 \), the Dempster rule of combination can in this case be used to combine the two as follows:

\[
m(A) = m_1 \oplus m_2(A) = \begin{cases} 0, & A = \emptyset \\ \frac{1}{1 - k} \sum_{B \ni C = A} m_1(B)m_2(C), & A \neq \emptyset \end{cases}
\]

Where \( k \) is defined as:

\[
k = \sum_{B \ni C = \emptyset} m_1(B)m_2(C)
\]

\( k \) is also a normalisation constant reflecting the degree of conflict between \( m_1 \) and \( m_2 \).
A CONCEPTUAL APPROACH TO UNCERTAIN BASED BENEFITS REALISATION PLANNING

1. QFD (URs Capture & analysis)
   - Establish Cause-Effect relationship using $D_k + R_j$ & $D_k - R_j$

2. Uncertain Information
   - ANP Alternatives Ranking
     - URs Data
     - DRs Data
     - Existing Use Data
     - Expert Feedback
     - Context Specific Risks

3. BoE
   - DST Modelling
     - URs Evidence
     - DRs Evidence
     - Use Data Evidence
     - Expert Evidence
     - Context Specific Evidence

4. Decision Support
   - Data Output
     - Expected Benefits
     - Deviation
     - Probability of exceeding Target Benefits-$p(Y > Y_{max})$

5. Sensitivity Analysis $Y > Y_{max}$

6. BRP

7. Optimisation of Inputs eg $B_{ui} + 1$
First Step is Requirements Management including raw data on user needs as basis for Design Decision Making - using quantitative approaches such as QFD, Utilitarian COPRAS, MOORA - (Yazdani et al., 2017)

- Key Step in Quantification of Requirements is to capture interdependences between them Using this Matrix.

\[
A = \begin{bmatrix}
c_1 & c_2 & \ldots & c_t & \ldots \\
b_{11} & b_{12} & \ldots & b_{1t} & \ldots \\b_{21} & b_{22} & \ldots & b_{2t} & \ldots \\
\vdots & \vdots & \ddots & \vdots & \ddots \\
b_{r1} & b_{r2} & \ldots & b_{rt} & \ldots \\
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0 & y_{12} & \ldots & y_{1j} & \ldots \\
y_{21} & 0 & \ldots & y_{2j} & \ldots \\
y_{31} & y_{32} & \ldots & y_{3j} & \ldots \\
\vdots & \vdots & \ddots & \vdots & \ddots \\
y_{n1} & y_{n2} & \ldots & y_{nj} & 0 \\
\end{bmatrix}
\]

A Utilitarian focus on decision making further establishes the trade-offs in decision making using cost-benefit analysis with this Matrix.
MODEL FOR UNCERTAINTY MODELLING – CONT...

• **STEP 2:** Model Input data as refine-able and uncertain variables ready for DS/ANP modelling.

• **STEP 3:** Define the Uncertainty Modelling parameters and Model the variables in the DS/ANP model

\[ u(\{b_i\}) = Pls(\{b_i\}) - Bel(\{b_i\}) \]

• **STEP 4:** Produce and Analyse Preliminary Results.

• **STEP 5:** Carry out Sensitivity Analysis

• **STEP 6:** Define the Benefits Realisation Planning (BRP) program from the sensitivity analysis.

• **STEP 7:** Iterate over uncertain information for results that do not meet criteria
CONCLUSIONS & LOOKING AHEAD

- Research represents a first step in the mathematical understanding and modelling of uncertainty in design.

- Research will aim to apply this understanding to the dynamic and uncertain process of social housing design.

- The application of mathematical uncertainty modelling represents a foundation for decision support filling gaps in current tools and applications for design decision making.

- Integrating the process of Requirements forecasting using Hidden Markov Modelling based on probability theory bring together complementary tools in focussing design process on utility of decision making.
User requirements in social housing change with time affected by such factors as technology, environment, sociocultural influences, geopolitics and physical/biological and societal/family/individual factors (Bolar et al., 2017).

Current approaches in social housing design decision making however do not attempt to predict these changes; merely attempting address current needs.

There is need for mathematical models for prediction of changing user needs during social housing design decision making.
HIDDEN MARKOV MODELLING (HMM)

• Probabilistic Hidden Markov Modelling (HMM) allows for integration with QFD’s requirements management process with automated prediction of changing use situations using emission and transition probabilities (Bolar et al., 2017).

• Current approaches in social housing design decision making however do not attempt to predict these changes; merely attempting address current needs.

• There is need for mathematical models for prediction of changing user needs during social housing design decision making.
HIDDEN MARKOV MODELLING (HMM)

• According to conditional probability the transition probability such that the probability of $X_t$ being in state $j$ given that $X_{t-1}$ was in $i$ for the transition probability matrix (TPM) is defined as (Asadabadi, 2017)

$$P[X_t = j|X_{t-1} = i] = P_{ij}^t$$

• A predictive mechanism for user requirements changes is thus as follows:
HIDDEN MARKOV MODELLING (HMM)

If the condition states set is such that \( S = \{s_1, s_2, \ldots, s_n\} \) with corresponding observed parameters \( O = \{o_1, o_2, \ldots, o_k\} \), \( 1 \leq i \leq n \) and \( 1 \leq j \leq k \). If \( \{X\} \) is the representation of the Markov chain \( P_{ij}^{(0)} \) is defined as the absolute probability such that \( s_i \) is in \( t_0 \). The transition probabilities so that \( s_i \) transits to \( s_1 \) is then represented by:

\[
A = \begin{bmatrix}
P_{s_1|s_1} & P_{s_1|s_2} & P_{s_1|s_3} & \cdots & P_{s_1|s_m} \\
P_{s_2|s_1} & P_{s_2|s_2} & P_{s_2|s_3} & \cdots & P_{s_2|s_m} \\
P_{s_3|s_1} & P_{s_3|s_2} & P_{s_3|s_3} & \cdots & P_{s_3|s_m} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
P_{s_m|s_1} & P_{s_m|s_2} & P_{s_m|s_3} & \cdots & P_{s_m|s_m}
\end{bmatrix}
\]  

The corresponding emission matrix for the output \( o_j \) given that the current state is \( s_i \) is as below

\[
B = C_{re} \begin{bmatrix}
P_{o_1|s_1} & P_{o_1|s_2} & P_{o_1|s_3} & \cdots & P_{o_1|s_m} \\
P_{o_2|s_1} & P_{o_2|s_2} & P_{o_2|s_3} & \cdots & P_{o_2|s_m} \\
P_{o_3|s_1} & P_{o_3|s_2} & P_{o_3|s_3} & \cdots & P_{o_3|s_m} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
P_{o_m|s_1} & P_{o_m|s_2} & P_{o_m|s_3} & \cdots & P_{o_m|s_m}
\end{bmatrix}
\]

Where the probabilities \( P_{s_i|s_1} \) and \( P_{o_1|s_2} \) are empirically determined and \( C_{re} \) is the credibility factor applied to represent confidence in the empirical sets and \( \sum_{i=1}^{m} P_{s_j|s_i} = 1 \) and \( \sum_{k=1}^{m} C_{re} P_{o_k|s_j} = 1 \). A HMM is thus the transition matrix \( A \) along with the probability \( P_{ij}^{(0)} \) associated with the \( s_j \) state while the emission matrix \( B \) is that with the probability \( P_{ij}^{(0)} \) associated with the observed outcome \( o_j \).
HIDDEN MARKOV MODELLING (HMM)

- Case example is a typical family probabilistic states of social housing use such as income cycles of low, medium, high and very high;
- Each of these states can determine the benefits realisation in these changing use cases of a social housing.
- These states $1, 2, \ldots, m$ can be captured and recorded at different times $t$.
- In HMM, state $i$ for low income at $t - 1$ is represented by $X_{t-1}$. (essentially, at any given time $t$, $i$ or $j$ can exhibit one state among $1, 2, \ldots, m$).
LOOKING AHEAD

The Mathematical Model Employs Quality Function Deployment in Requirements Management that are modelled using Probability theory - Dempster-Shafer Theoretic and Hidden Markov Modelling to model changing user and design Requirements to support design decision making in meeting utility of social housing amid use and process uncertainty.
THE END

Questions Please Welcome
REFERENCES


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