

THE SCALABILITY AND FLEXIBILITY OF QUALITATIVE ARCHI BOND GRAPHS FOR BUILDING SIMULATIONS

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Abstract

Qualitative Archi Bond Graphs (QABGs) are energy-based unified representations for buildings that can be used for building simulations at the early stage of designing. This paper presents an approach to their scalability and flexibility when applied to the simulation of the behaviour of buildings with complex spatial structures or building dynamics under time varying situations.

Keywords: bond graphs, qualitative, representation, scalability

1. Introduction

Current representations for buildings mainly focus on their static aspects such as spatial arrangements and arrangements of different building energy systems. The majority of these representations are applicable only at the final stage of building design when most of the data is already known. Designers use different representations for different building subsystems including space-people systems and building energy systems.

Bond graphs (Thoma 1975; 1990; Gawthrop and Smith 1996; Karnopp et al. 2000) combining graphical representations and mathematical equations are an energy-based systematic representation. They provide a unified approach to the modelling and analysis of the dynamics of hybrid multi-domain systems. Qualitative reasoning does not reason about a system in terms of the precise values but rather reasons at a qualitative level. It can be employed to build a knowledge model to represent the relationship between system structure and behaviour (Williams 1991; Werthner 1994; Wang and Linkens 1996).

Based on bond graphs, Gero and Tsai (2004; 2005) developed bond graphs for multiple domains (MBGs) that have the capacity to integrate multiple domains using the concepts of energy transformation and transduction. They further specialised MBGs to the domain of architecture to develop Archi Bond Graphs (ABGs). ABGs are capable of representing and simulating static system structures and dynamic behaviours of different building subsystems. Drawing on qualitative physics and using discrete symbols to represent dynamic properties of a system, Tsai and Gero (2006a;

2006b) developed qualitative Archi Bond Graphs (QABGs). Combining graphical representations and qualitative equations, QABGs provide a more general model, applicable to a wide range of differing conditions in building design.

The application of clusters for QABGs is introduced in this paper. It provides scalability and flexibility in using QABGs to simulate the behaviours of a building with more complex spatial structures or dynamics under time varying situations. This paper commences with a brief introduction to QABGs. This is followed by an outline of the clustering approach with illustrations of its application. An example shows QABGs with clusters applied to building simulation for a space-people system under time varying situations.

2. Qualitative Archi Bond graphs

ABGs and QABGs can be applied to buildings including space-people systems and different building energy systems, such as lighting system and hydraulic system. As with ABGs, QABGs consist of variables, elements and bicausal bonds. Details can be found in Gero and Tsai in (Gero and Tsai 2004; 2005; Tsai and Gero 2006a; 2006b).

Variables, Elements, and Bicausal Bonds

The definitions and units of the variables and elements of QABGs applied to building energy systems are very similar to those in regular bond graphs for the electrical, hydraulic and HVAC systems. Variables and elements defined for the space-people system are shown in Table 1.1 (Gero and Tsai 2004; 2005) and Table 1.2 (Tsai and Gero 2006a; 2006b) respectively. Elements of QABGs (QL) can be categorized into 1-port elements and multi-port elements. They are terminals (T) and junctions (J) respectively, Table 2.

1.1 Variables

effort, e	unit people-energy
flow, f	people-flow
momentum, p	people-impulse
displacement, q	people-change
power, P	people-energy-flow
energy, E	people-energy

1.2 Elements

S-element	people-energy source
I-element	space-potential, passage
C-element	space-capacitor, room
R-element	space-resistor
CR-element	controller, door
M-element	meter
B-element	building component
TF, TD	energy transformer and transducer
0-, 1-junction	space-junction
EC-element	energy controller

Table 1. Variables and elements for space-people system

1-port element: Terminal (T)			Multi-port element: Junction (J)
Energy source (T _s)	Energy operator (T _o)		
Active 1-port	Passive 1-port	Additive 1-port	
Source, S	Inductor, I	Controller, CR	Transformer, TF
	Capacitor, C	Meter, M	Transducer, TD
	Resistor, R	Building component, B	0-junction
			1-junction
			Energy controller, EC

Table 2. QAB elements

An ABG bicausal bond is attached with two half-arrows and two causal strokes at both ends of a bond, as well as two pairs of effort and flow, which makes it different

from the bicausal bonds of Gawthrop (1995). It represents both flow, e.g. people-flow and building energy flow, and the caused effort, e.g. unit people-energy variation and effort of building energy variation, in two-directional movements, moving into and out of a space or device simultaneously.

Qualitative equations of QABGs

Qualitative equations of QABGs, associating qualitative values with qualitative operations, provide a mechanism for reasoning about energy transformations and transductions within systems, as well as energy interactions between systems. Qualitative operations in QABGs include addition, subtraction, multiplication, division, and equality: $\{+, -, \times, \div, =\}$. Qualitative values of QABGs include $\{[-], [-], [0], [+], [++], [d]\}$. $[0]$ is the boundary between $[-]$ and $[+]$, negative and positive values. $[-]$ and $[+]$ are large negative and large positive values for a variable respectively. $[d]$ expresses a dependent value which is determined by different conditions, dependent on the context, for the qualitative operations. Qualitative values of variables for bond graphs have been discussed elsewhere (Wang and Linkens 1996; Ghiaus 1999; Lo 2003). Qualitative values in QABGs apply to:

- power variables, i.e. effort and flow, and M- and B-elements, $[-]$, $[0]$, and $[+]$ represent different abnormal behaviours, while $[-]$ and $[+]$ denote the normal behaviours;
- I, C, R and CR elements, $[+]$ denotes the normal behaviour;
- R and CR elements, $[+]$ denotes element blocked, and $[0]$ denotes element leakage or short circuit

QABG qualitative equations contain constitutive relationships and all the necessary information about a physical system. For QABGs, numerical parameters in equations are replaced by symbols, i.e. qualitative values. Details of constitutive equations of QABGs can be found in Tsai and Gero (2006a; 2006b). They represent system structures and dynamic behaviours of people and variations of people-energy, or dynamic movements of building energy and variations of building energy.

A QABG model for a building combines graphical representations and qualitative equations. QABGs model construction for a building system starts from a building subsystem, to multi-subsystems of a building and then an integrated unified building system. QABGs have been applied to the simulation of building dynamics (Tsai and Gero 2006a) and to energy interactions between building subsystems (Tsai and Gero 2006b). However, when QABGs are applied to a building system with more complex building subsystem structures or building dynamics under time varying situations, the generations of graphical representations and qualitative equations as well as the simulations and inferences become very complex and increase in scale. Applications of clusters for QABGs provide a means to control both the increase in scale and increase in complexity.

3. Scalability of QABGs

A qualitative graphical representation and the quantitative equations of a building subsystem can be divided into numerous clusters (CI). In general, 0-junctions and 1-junctions are the places where a QABG of a building system can be divided. There are two cluster types of a building subsystem: essential clusters, Cl_{ess} , and additional

clusters, Cl_{add} . An essential cluster, Cl_{ess} , is a cluster included in a building subsystem in a series of qualitative building simulations for every situation. In contrast, an additional cluster, Cl_{add} , is a cluster only for some situations. In a series of qualitative simulations of building subsystems in different situations, a building subsystem might consist of both types of clusters, i.e. essential and additional clusters, Eq (1).

$$BS_s(t) = Cl_{ess}(t) + Cl_{add}(t) \quad (1)$$

BS_s : building subsystem

t : time period

$Cl_{ess}(t)$ = essential cluster(s)

$Cl_{add}(t)$ = additional cluster(s)

The combination of essential and additional clusters represents the dynamic behaviours within the static system structure of the building subsystem in a series of building simulations for different situations. For instance, a building subsystem of a space-people system, $S-P_{sys}$, is divided into $m+n$ clusters, Eq (2). m represents the sets of essential clusters and n represents the sets of additional clusters of this space-people system.

$$S-P_{sys}(t) = Cl^{(m+n)}(t) = Cl_{ess}^{(m)}(t) + Cl_{add}^{(n)}(t) \quad (2)$$

m = the sets of essential clusters, if $m = \{a, b, g\}$

n = the sets of additional clusters, if $n = \{c, d, e, f\}$

Then, in simulations of this space-people system in different situations, each qualitative building simulation and analysis consists of m essential clusters, $Cl_{ess}^{(m)}$, and n' additional clusters, $Cl_{add}^{(n')}$, $n' \subseteq n$, Eq (3).

$$S-P_{sys}(t) = Cl_{ess}^{(m)}(t) + Cl_{add}^{(n')}(t), \quad n' \subseteq n = \{c, d, e, f\} \quad (3)$$

Clusters provide the scalability and flexibility for QABGs. The construction of a building subsystem using clusters can be scaled and recombined to represent system dynamics in any time period. The scalability of clusters lies in the construction of a building subsystem. It can include only essential cluster(s), $Cl_{ess}^m(t_1)$, or both essential cluster(s) and additional cluster(s), $Cl_{ess}^m(t_2) + Cl_{add}^{n_2}(t_2)$, or the same essential cluster(s) and additional cluster(s) in different simulation time periods, $Cl_{ess}^m(t_2) + Cl_{add}^{n_2}(t_2) = Cl_{ess}^m(t_3) + Cl_{add}^{n_3}(t_3)$. The flexibility of clusters for different situations is because any additional cluster of the building subsystem is replaceable. That is, essential clusters of the building subsystem remain the same for a series of qualitative building simulations for different situations but additional clusters can be different, such as $Cl_{ess}^m(t_1) + Cl_{add}^{n_1}(t_1) \neq Cl_{ess}^m(t_2) + Cl_{add}^{n_2}(t_2)$, where $Cl_{ess}^m(t_1) = Cl_{ess}^m(t_2)$ but $Cl_{add}^{n_1}(t_1) \neq Cl_{add}^{n_2}(t_2)$.

When any dynamic behaviour within the subsystem is changed, e.g. movement of people-flow and building energy flow as well as variation of unit people-energy and effort of building energy, the corresponding qualitative values of QABG power variable(s), i.e. flow (f) and effort (e), within the clusters of the building subsystem will also be changed. Then, the qualitative simulation output of the new dynamic system state can be obtained by applying the changed qualitative values of power variables into qualitative equations of clusters of the changed system state.

4. Application of Clusters to QABG Simulations for System Dynamics of a Space-People System

In the following, QABGs with clusters are applied to a building simulation of a space-people system under time varying situations. Figure 1(a) shows the drawing of the spatial system of a building. This spatial system consists of a number of doors, labelled CR1 to CR9, and rooms with different functions, including a lobby (C1), an office (C2), a foyer (C3), a function room (C4), a shop and bar (C5), and toilet 1 (C6) and toilet 2 (C7). Source (S) represents the outside which people move from into the building. The drawing of the spatial system is converted into the QABG graphical representation presented in Figure 1(b). The initial qualitative equations of this space-people system are then generated to represent the structure of the spatial system and people behaviours within this spatial system. The qualitative equations represent people-flow moving in the spatial system in two directions, the same direction as and the opposite direction to people-flow moving from the outside into the building, then into different rooms.

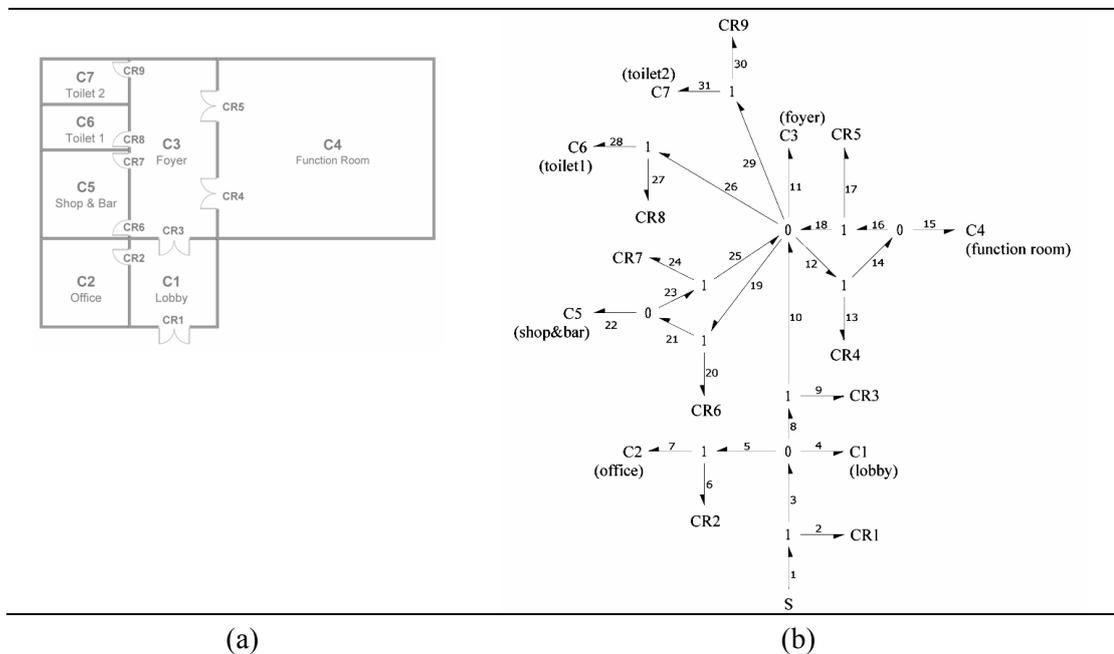


Figure 1. (a) Drawing of the spatial system of a building, and
(b) QABG graphical representation of the space-people system

The QABG graphical representation and qualitative equations of the space-people system can be divided into a number of clusters where different components of the space-people system joint. Each cluster of the space-people system, associated with a sub-graphical representation with corresponding qualitative equations, represents partial people behaviours and unit people-energy variations. Figure 2 shows the graphical representation of the clusters, Clusters a to g.

Scenarios

Six scenarios, Scenarios 1 to 6, are presented, Figure 3.

- **Scenario 1** (S1) consists of Clusters a, b, c, and e, $C1^{(a+b+c+e)}$, Figure 3(a). The time period of Scenario 1 is between t_0 and t_1 . During this period, people-flow moves from the outside through door CR1 into the lobby (C1) and out of the lobby to

the outside, $CI^{(a)}$, through door CR3 from the lobby into the foyer (C3) and out of the foyer back to the lobby, $CI^{(c)}$, as well as from the foyer through door CR6 into the shop and bar (C5) and through door CR7 out of the shop and bar back to the foyer, $CI^{(e)}$. In addition, people-flow moves through door CR2 from the lobby into the office (C2) and out of the office back to the lobby, $CI^{(b)}$.

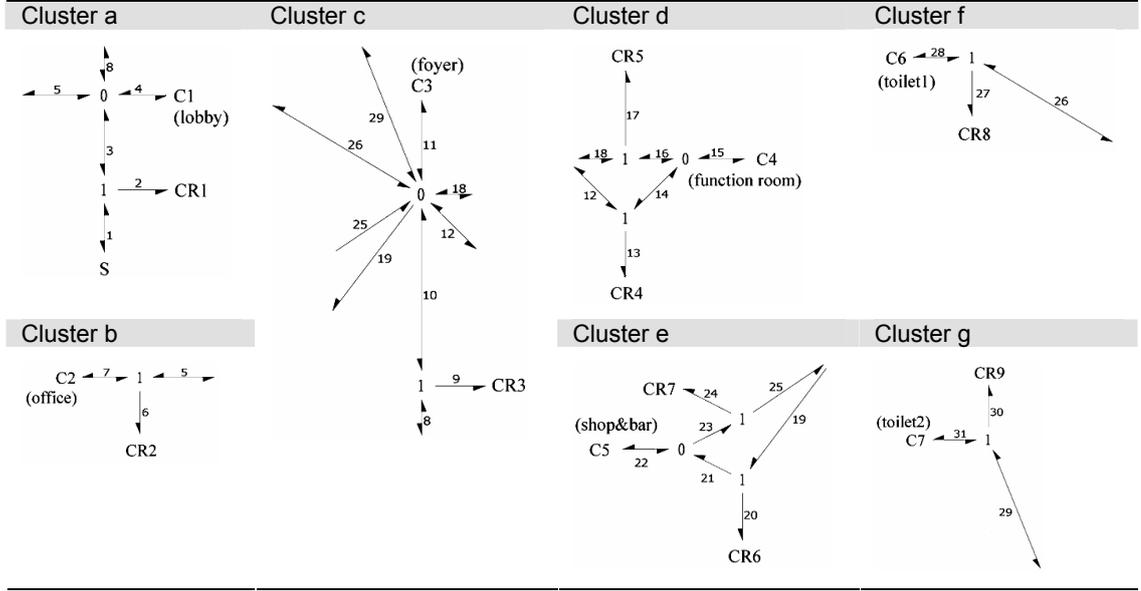


Figure 2. QABG graphical representation of Clusters a to g

- Scenario 2 (S2)** consists of Clusters a, b, c, e, f, and g, $CI^{(a+b+c+e+f+g)}$, Figure 3(b). The time period of Scenario 2 is between t_1 and t_2 . During this period, people-flow moving into and out of the lobby (C1), $CI^{(a)}$, into and out of the foyer (C3), $CI^{(c)}$, and into and out of the shop and bar (C5), $CI^{(e)}$, is similar to that in Scenario 1. In addition, people-flow moves through door CR2 from the lobby into the office (C2) and out of the office back to the lobby, $CI^{(b)}$, through door CR8 into and out of toilet 1 (C6), $CI^{(f)}$, and through door CR9 into and out of toilet 2 (C7), $CI^{(g)}$.
- Scenario 3 (S3)** consists of Clusters a, b, c, d, e, f, and g, $CI^{(a+b+c+d+e+f+g)}$, Figure 3(c). The time period of Scenario 3 is between t_2 and t_3 . During this period, people-flow moving into and out of the lobby (C1), $CI^{(a)}$, into and out of the foyer (C3), $CI^{(c)}$, and into and out of the shop and bar (C5), $CI^{(e)}$, is very similar to that in Scenario 1. In addition, people-flow moves from the foyer through doors CR4 and CR5 into and out of the function room (C4), $CI^{(d)}$, through door CR8 into and out of toilet 1 (C6), $CI^{(f)}$, and through door CR9 into and out of toilet 2 (C7), $CI^{(g)}$. Door CR2 is closed but there are some people in the office (C2).
- Scenario 4 (S4)** consists of Clusters a, b, c, d, e, f, and g, $CI^{(a+b+c+d+e+f+g)}$, Figure 3(d). The time period of Scenario 4 is between t_3 and t_4 . Although clusters of Scenario 4 are the same as Scenario 3, people-flow moving in the space-people system is not all the same in these two scenarios. For instance, in Scenario 4, people-flow moves into and out of the office (C2). Doors CR4 and CR5 are closed but there are some people in the function room (C4), $CI^{(d)}$.

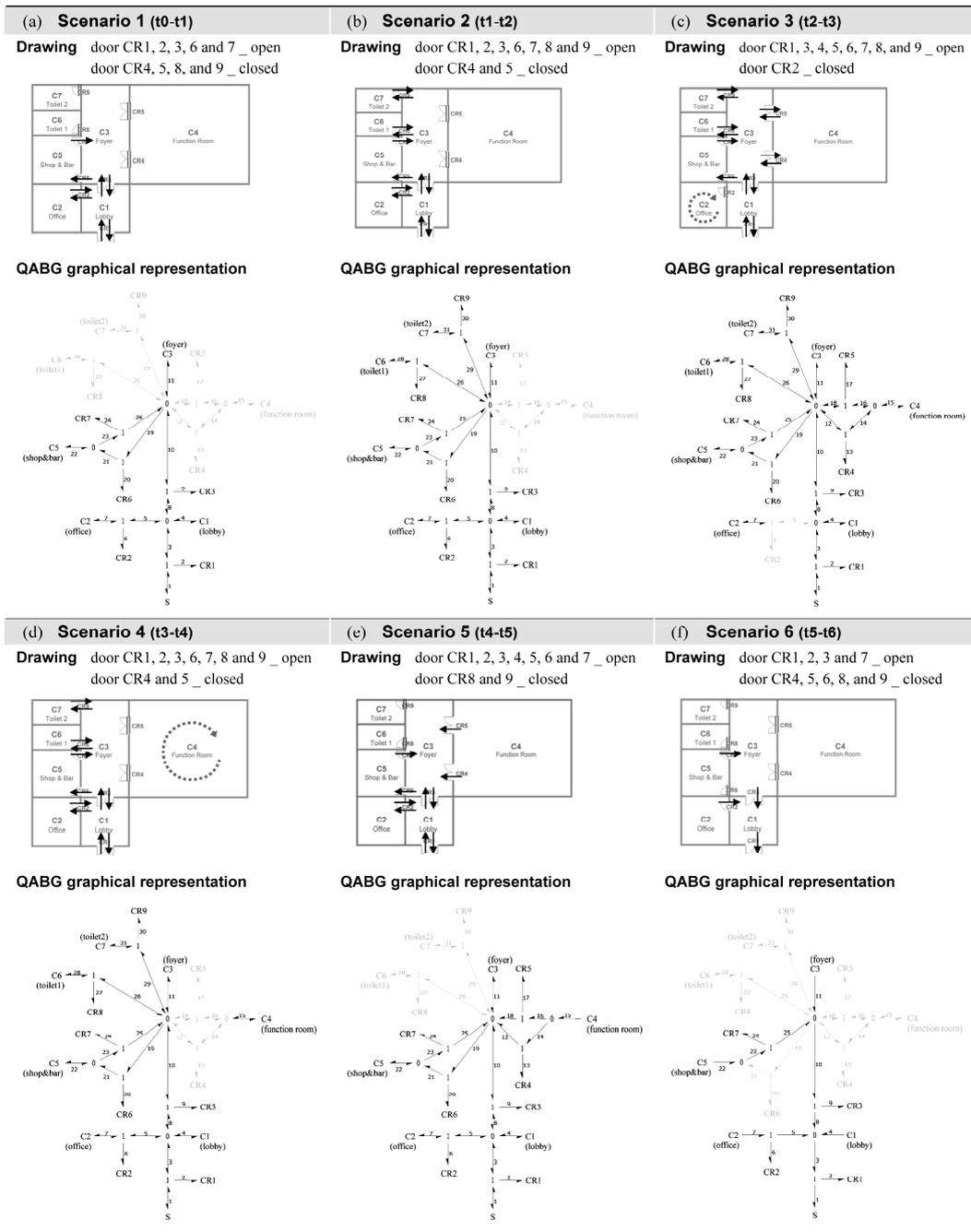


Figure 3. Plan drawings and QABG graphical representations of Scenarios 1-6

- Scenario 5** (S5) consists of Clusters a, b, c, d, and e, $CI^{(a+b+c+d+e)}$, Figure 3(e). The time period of Scenario 5 is between t4 and t5. During this period, people-flow moving into and out of the lobby (C1), $CI^{(a)}$, into and out of the foyer (C3), $CI^{(c)}$, and into and out of the shop and bar (C5), $CI^{(e)}$, is very similar to that in Scenario 1. In addition, people-flow moves through door CR2 from the lobby into the office (C2) and out of the office back to the lobby, $CI^{(b)}$. It also moves through doors CR4 and CR5 out of the function room (C4) to the foyer, $CI^{(d)}$.
- Scenario 6** (S6) consists of Clusters a, b, c, and e, $CI^{(a+b+c+e)}$, Figure 3(f). The time period of Scenario 6 is between t5 and t6. During this period, there is no people-

flow moving into the building. People-flow moves in the opposite direction to people-flow moving from the outside into the building. It moves through door CR7 out of the shop and bar (C5), $CI^{(e)}$, through door CR3 out of the foyer (C3), $CI^{(c)}$, through door CR2 out of the office (C2), $CI^{(b)}$, and through door CR1 out of the lobby to the outside, the source (S), $CI^{(a)}$.

Essential and Additional Clusters of Scenarios

Table 3 shows people behaviours around different doors, doors CR1 to CR9, and in different rooms, rooms C1 to C7, in every time period from Scenario 1 to Scenario 6. Essential clusters and additional clusters of each scenario, Scenarios 1 to 6, are shown in Table 4.

door(room) scenario	CR1(C1)	CR2(C2)	CR3(C3)	CR4 (C4) CR5	CR6 (C5) CR7	CR8(C6)	CR9(C7)
S1 (t0-t1)	↑↓(⊕)	↑↓(⊕)	↑↓(⊕)	- (⊗) -	↑(⊕) ↓	- (⊗)	- (⊗)
S2 (t1-t2)	↑↓(⊕)	↑↓(⊕)	↑↓(⊕)	- (⊗) -	↑(⊕) ↓	↑↓(⊗)	↑↓(⊗)
S3 (t2-t3)	↑↓(⊕)	- (⊕)	↑↓(⊕)	↑↓(⊕) ↑↓	↑(⊕) ↓	↑↓(⊗)	↑↓(⊗)
S4 (t3-t4)	↑↓(⊕)	↑↓(⊕)	↑↓(⊕)	- (⊕) -	↑(⊕) ↓	↑↓(⊗)	↑↓(⊗)
S5 (t4-t5)	↑↓(⊕)	↑↓(⊕)	↑↓(⊕)	↓(⊕) ↓	↑(⊕) ↓	- (⊗)	- (⊗)
S6 (t5-t6)	↓(⊕)	↓(⊕)	↓(⊕)	- (⊗) -	- (⊕) ↓	- (⊗)	- (⊗)

C: room; CR: door; S: scenario;
 ↑↓ : people-flow (↑ : moving into; ↓ : moving out of; - : no people-flow, door is closed)
 ⊕ : people within the room
 ⊗ : no people within the room

Table 3.
People behaviour around different doors and rooms in Scenarios 1 to 6.

	Essential cluster	Additional cluster
Scenario 1: $CI^{(a+b+c+e)}$	$CI_{ess}^{(a+c+e)}$	$CI_{add}^{(b)}$
Scenario 2: $CI^{(a+b+c+e+f+g)}$	$CI_{ess}^{(a+c+e)}$	$CI_{add}^{(b+f+g)}$
Scenario 3: $CI^{(a+b+c+d+e+f+g)}$	$CI_{ess}^{(a+c+e)}$	$CI_{add}^{(b+d+f+g)}$
Scenario 4: $CI^{(a+b+c+d+e+f+g)}$	$CI_{ess}^{(a+c+e)}$	$CI_{add}^{(b+d+f+g)}$
Scenario 5: $CI^{(a+b+c+d+e)}$	$CI_{ess}^{(a+c+e)}$	$CI_{add}^{(b+d)}$
Scenario 6: $CI^{(a+b+c+e)}$	$CI_{ess}^{(a+c+e)}$	$CI_{add}^{(b)}$

Table 4.
Essential and Additional Clusters of Scenarios 1 to 6

Qualitative Simulation Output

By assigning qualitative values of normal and abnormal behaviours of people-flow and unit people-energy to qualitative equations in essential and additional clusters of the space-people system, and following energy inference processes, the qualitative building simulation of scenarios will produce qualitative outputs of unit people-energy variations in rooms, i.e. space-capacitor (C), of the building under time varying situations. Normal means an average, stable or gradually changed condition and abnormal means there is a sudden change. Details of inference processes have been illustrated in (Tsai and Gero 2006a; 2006b).

Figure 4 shows qualitative simulation results of people-flow, unit people-energy, people-change, and people-energy in different rooms, C1 to C7, of the space-people system with time variations, from time interval t0-t1 to t5-t6. The results for the lobby (C1) are the same as those for the foyer (C3). The results for toilet 1 (C6) are the same as those for toilet 2 (C7). The results for each room include those for people moving into and out of the room as well as those for people within the room.

The results for people moving into and out of the room:

- The qualitative values are [0] for people-flow, unit people-energy, people-change, and people-energy in the situations when the door of the room is closed.

There is no people-flow, no unit people-energy variation, no people-change, and no people-energy variation.

- People-flow moves in the space-people system at a normal velocity. The qualitative value is [+], $f(nT)=[+]$. The qualitative value of people-flow is decreasing when people-flow moving into the room is less than that it moving out of the room.

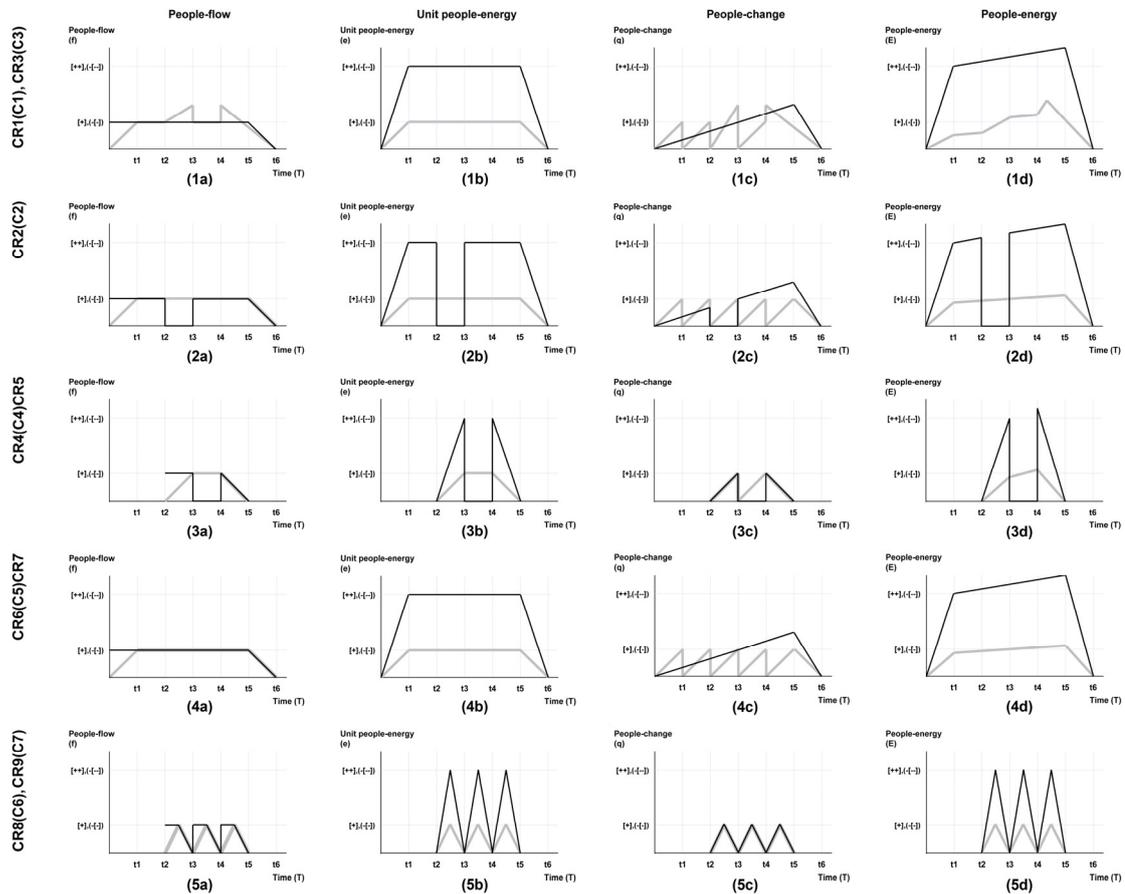


Figure 4. Qualitative simulation outputs of people-flow (f), unit people-energy (e), people-change (q), and people-energy (E) in different rooms of the space-people system from time interval t_0-t_1 to t_5-t_6

- People-flow moving into a room causes a sudden increase of unit people-energy variation in the room they move into, $e(nT)=[++]$. In contrast, people-flow moving out of a room causes a sudden decrease of unit people-energy variation in the room they move out of, $e(nT)=[--]$.
- To infer the qualitative values of people-change and people-energy variation, people-change equals people-flow times time, $q = f \times t$ and people-energy equals people-change times unit people-energy, $E = q \times e$.

The qualitative simulation outputs of people within the room:

- People moving into a room, the qualitative value of people-flow increases from [0] until it reaches a stable condition, the qualitative value is [+].
- People move via one room into another room, for instance, they move via the lobby into the office, the qualitative value of people-flow in the room which they move through will increase until it reaches a stable condition.

- People-flow within the room causes unit people-energy variation. The qualitative value of unit people-energy variation increases from [0] until it reaches a stable condition, the qualitative value is [+].
- The qualitative values of people-change and people-energy are obtained by inferring constitutive relations of $q = f \times t$ and $E = q \times e$ respectively.

5. Conclusion

This paper presents QABGs with clusters applied to the simulation of the space-people system in a building to determine some aspects of the building's behaviour. The results demonstrate the capacity of the approach to produce qualitative simulations of buildings. In a further paper, we will present QABGs with clusters applied to simulation of interactions between the space-people system and different energy systems in more complex situations of buildings.

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