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QUALITATIVE ARCHI BOND GRAPHS FOR BUILDING SIMULATION OF PEOPLE BEHAVIOUR AND ENERGY VARIATION

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ABSTRACT

This paper presents the construction and application of an approach called qualitative Archi Bond Graphs developed as a unified representation for building design that can be used for simulation. The construction of qualitative Archi Bond Graphs includes graphical representations and qualitative equations. Qualitative Archi Bond Graphs can be applied in the conceptual stage of building design.

INTRODUCTION

A building is a complex combination of elements and processes, which can be viewed as a system. A building system consists of a number of building constructs such as spatial arrangement, circulation arrangement, and building energy arrangements, including electricity, hydraulics, HVAC, and light energy. They can be treated as subsystems of a building system. Currently, different representations are used for different building constructs when designers develop a building design project. The majority of representations can only be employed in the intermediate and final stages of design. Many of them focus on the static aspect of buildings. Building dynamics include people flow, goods flow, and energy flow which also need to be represented since a building is constructed for people and/or for goods. Therefore, a unified representation of building design is needed. It should be able to represent both static and dynamic aspects of buildings and be applied in the conceptual design stage. The development of a unified representation of building design is not only for better communication between the various designers but also for better understanding, formulation, and evaluation of interactions between different building constructs.

Qualitative reasoning is a powerful model-based reasoning method which allows for reasoning with incomplete and weak numerical information. It does not reason exclusively about a system in terms of the precise values and interrelationships between parameters but rather reasons about these values and interrelationships at a qualitative level. Qualitative reasoning can be employed to build a deep-level knowledge model to represent the relationship between system structure and behaviour (Williams 1991; Werthner 1994; Wang and Linkens 1996). Current research into qualitative representation and modelling for architectural design focuses on the qualitative aspects of shapes, objects and internal organization of architectural plans (Gero and Park 1997; Gero and Damski 1999; Gero and Jupp 2003).

Archi Bond Graphs (ABGs) (Gero and Tsai 2004; 2005) have been developed as a qualitative and quantitative energy-based unified representation for building design. They can be used in the early design stage as well as in the intermediate and final design stages. ABGs have capacities to represent structures of different building constructs of a building, such as spatial arrangement and building energy arrangements, and to represent and simulate people behaviours with people-energy variations and building energy flows with building energy variations within these structures. In addition, ABGs can represent and simulate interactions between different building constructs.

Qualitative Archi Bond Graphs (QABGs) draw on qualitative physics and use discrete symbols to represent and simulate dynamic properties of the system. QABGs which consist of graphical representations and qualitative equations with qualitative values provide a more general model, applicable to a wide range of different conditions in building design. Applications of QABGs are intended to focus on the conceptual stage of building design.

This paper describes QABGs applied to space-people system on the simulation of people behaviour and people-energy variation within a building. It commences with the depiction of the development of a unified representation for building design, from regular bond graphs (RBGs), to bond graphs for multiple domains (MBGs) and bond graphs in the domain of architecture: Archi Bond Graphs (ABGs). The construction of ABGs is then illustrated, followed by the construction of QABGs. An application of QABGs for preliminary building simulation of people behaviour and people-energy variation within a space-people system is presented.

RBGS, MBGS, AND ABGS

Bond graphs introduced by Henry Paynter in the early 1960's (Thoma 1975; 1990; Gawthrop and Smith 1996) are a class of graphical languages and systematic representations which provide a unified approach to the modelling and analysis of the dynamics of hybrid multi-domain systems. As a modelling tool, bond graphs can be used in the conceptual design stage. Bond graphs consist of variables, elements, and constitutive relations. In the bond graph formalism, the determination of the input and output sets is defined as a causality assignment procedure.

Bond graphs have been applied in many physical domains such as mechanics, electronics and hydraulics. Bond graphs applications in architecture are limited to greenhouse dynamic modelling (Bot and van Dixhoorn 1978) and HVAC systems design and simulation (Zeiler 1997).

Bond graphs are called regular bond graphs (RBGs) in our research. We have developed bond graphs for multiple domains (MBGs) that have the capacity to integrate and be applied in multiple domains. Within MBGs, energy, E, is defined in a broad sense as the ability and/or power to do or achieve something. The definition of displacement, q, is change caused by energy in a general sense. Based on that, other variables and elements of MBGs are defined (Gero and Tsai 2004; 2005).

ABGs, focused on the domain of architecture, are used to represent three major aspects of a building: as a collection of objects, as a container for people and goods, and as a container and transformer of processes.

ARCHI BOND GRAPHS

ABGs include graphical representations and mathematical equations that can be used to represent static and dynamic aspects of buildings: structures of space arrangement and building energy arrangement as well as behaviours of people and building energy within these structures.

ABGs consist of variables, elements, constitutive relations, and bicausal bonds. We give new definitions to ABG variables and elements as well as develop new elements. Constitutive relations constructing the relationships between elements and variables are represented by mathematical equations. ABG bicausal bonds have the capacity to represent behaviours of people/building energy moving into and out of a space within a building and the associated energy variations simultaneously.

ABG variables and elements

ABGs can be applied to space-people systems and building energy systems. In ABGs for different building energy systems, the definitions and units of variables and elements are very similar to those in RBGs for systems of electricity, hydraulics, and HVAC. For space-people system, ABG variables of energy and displacement are defined as (Gero and Tsai 2004; 2005):

- Energy, E: *people-energy* is the sum of variations of all sub-amounts of people-energy caused by all sub-groups of people moving within a building during a period of time.
- Displacement, q: *people-change* is the total number of people changes within a building during a period of time.

ABG variables of effort, flow, momentum and power for space-people system are then defined as follows:

- Effort, e: *unit people-energy* is the average amount of variation of people-energy caused by one person moving within a building in a unit of time.
- Flow, f: *people-flow* is the total number of people changes in a unit of time.
- Momentum, p: *people-impulse* is the average amount of variation of people-energy caused by one person moving within a building during a period of time.
- Power, P: *people-energy-flow* is the total amount of variation of people-energy caused by all people moving within a building in a unit of time.

Table 1 shows ABG variables for space-people system.

Table 1 ABG variables for space-people system
(Gero and Tsai 2005)

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

ABG elements (L) are categorized into 1-port and multi-port elements, Eq (1). 1-port elements are source (S), i.e. source of effort (S_e) and source of flow (S_f), inducer (I), capacitor (C), resistor (R), controller (CR), meter (M), and building construction/component (B), i.e. exterior building construction/component (B_e) and interior building construction/component (B_i). Multi-port elements include transformer (TF), transducer (TD), 0-junction, and 1-junction.

$$L = \{S, I, C, R, CR, M, B, TF, TD, 0, 1\} \quad (1)$$
$$S = \{S_e, S_f\}$$
$$B = \{B_e, B_i\}$$

In ABG 1-port elements, the S-element is an active element, I, C, and R elements are passive elements, and CR, M, and B elements are additive elements. For space-people system, ABG elements of S, I, C, and R are defined as follows:

- S-element: *people-energy source* represents the point where people move from.
- I-element: *space-potential* stores people-impulse and pushes people to move within the building. ABG I-element represents passages such as corridors, ramps, steps and stairs within a building.
- C-element: *space-capacitor* treats space within a building as a container of people. ABG C-element represents different types and scales of rooms within a building.
- R-element: *space-resistor* represents the restriction that affects people moving between spaces within the building.

CR, M, and B elements are introduced in ABGs for space-people system and building energy systems as controller, meters, and building construction/ component respectively.

- CR-element: *controller* does not dissipate energy but affects energy flow, e.g. slows down or stops energy flow. It represents doors in space-people system. In building energy systems, it is a switch in lighting system and a tap in water supply system.
- M-element: *meter* measures the variation(s) of people-energy and/or building energy at specific points in the building.
- B-element: *building construction/component* affects building energy consumptions. B-element includes B_e and B_i elements. The former is placed in-between exterior and interior spaces, i.e. external walls of a building, and the latter is placed in-between different interior spaces, i.e. internal walls or floors.

TF and TD elements of ABGs are energy transformer and transducer respectively. TF-element conserves power and transmits the factor of power, i.e. effort (e) and flow (f), with power scaling, while TD-element represents the mechanism where different types of energy are transformed.

ABG 0-junction and 1-junction are parallel junction and serial junction respectively. For space-people system they are treated as *space-junctions* (Gero and Tsai 2005), connecting one space to one or more other spaces. The differences between these two space-junctions are

- 0-junction implies that people may progress to spaces different from the space where they came from.
- 1-junction implies that people are not able to progress to other spaces except returning to the space where they came from.

Table 2 shows ABG elements for space-people system.

Table 2 ABG elements for space-people system

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 construction/component
TF, TD	energy transformer and transducer
0-, 1-junction	space-junction

ABG bicausal bond

Causality in RBGs establishes the cause and effect relationships between the factors of power. In each bond, the input and output are characterized by the causal stroke. We extend the bicausal bond introduced by Gawthrop (1995) to develop bicausal bonds in ABGs. Different from causality in RBGs and Gawthrop's, an ABG bicausal bond is attached with two pairs of effort and flow to represent people-flow or building energy flow as well as the efforts caused by the flows of people or building energy moving into and out of a space/device simultaneously, Figure 1.

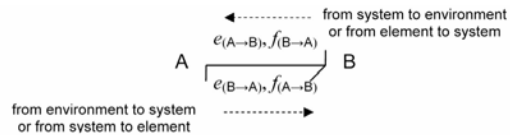


Figure 1 ABG bicausal bond (Gero and Tsai 2005)

QUALITATIVE ARCHI BOND GRAPHS

A qualitative approach based on both physical laws and expert knowledge/rules is more applicable when mathematical models are difficult to obtain or unavailable (Lo et al. 2002; 2004). To reason with incomplete and weak numerical information, the construction of QABGs associates graphical representations with qualitative equations. A QABG graphical representation consists of elements and element-link-relationships. Qualitative equations of ABGs involving qualitative values and qualitative operations provide a mechanism for reasoning about energy transfer and transformation within the system.

Elements and element-link-relationships in QABGs

ABG elements and linking bonds represent nodes and arcs in QABGs. An arc has two pairs of power variables: effort (e) and flow (f). Nodes can be terminals (T) or junctions (J). Terminals include energy source (T_S) and energy operators (T_O), i.e. inductor (T_I), capacitor (T_C), resistor (T_R), controller (T_{CR}), meter (T_M), and building construction/component (T_B). Junctions include transformer (J_{TF}), transducer (J_{TD}), 0-junction (J_0), and 1-junction (J_1). QABG terminals and junctions are shown in Eq (2).

$$
\begin{aligned}
&QL = T \cup J \qquad (2)\\
&T = T_S \cup T_O\\
&T_O = \{T_I, T_C, T_R, T_{CR}, T_M, T_B\}\\
&J = \{J_{TF}, J_{TD}, J_0, J_1\}
\end{aligned}
$$

The element-link-relationships of QABGs can be in different forms including the link-relationships between terminal and junction as well as between junctions.

Qualitative values and operations of QABGs

The qualitative value of QABGs for variables can be either as a landmark value or as an open interval between two adjacent landmarks in the qualitative space of the variable. If *x* is a variable for QABGs, the sign of its value is [*x*]. 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; and [d] expresses a dependant value which is determined by different conditions for the qualitative operation.

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.

Qualitative operations in QABGs correspond to the standard operators of real numbers including addition, substraction, multiplication, division, and equal: {+, -, ×, ÷, =}. Table 3 shows qualitative operations in QABGs. Assume |[--]| ≅ [++] and |[-]| ≅ [+].

Qualitative equations of QABGs

QABG qualitative equations provide the conceptual function to indicate the elements' locations in the system structure and their individual behaviours as well as interactions with the behaviour of the whole system. These equations connect constitutive relationships and contain all the necessary information about a physical system. For QABGs, numerical constants in equations are replaced by symbol names, qualitative values, which correspond to human states of incomplete knowledge.

Constitutive equations of QABGs represent system structures and behaviours of people/building energy:

- I, C, R elements associated with effort (e) and flow (f), their relationships are

$$e = R \times f\ , \quad f = C\frac{d}{dt}e\ , \quad e = I\frac{d}{dt}f \qquad (3)$$

- for elements of I, C, R, and CR, I-element stores p-variable, C-element stores q-variable, R-element consumes energy, and CR-element controls flow of energy, t is a sampling time period, where $t_2 > t_1$

Inductor, I: $e(t_2) = I \times (f(t_2) - f(t_1))$ (4)

Capacitor, C: $f(t_2) = C \times (e(t_2) - e(t_1))$ (5)

Resistor, R: $e(t) = R \times f(t)$ (6)

Controller, CR: $e(t) = CR \times f(t)$ (7)

- for elements of TF and TD, the former receives either effort or flow information in one bond and generates the same information in another bond, Eq (8), and the latter establishes relationships between flow to effort and effort to flow, Eq (9).

Transformer, TF: $e_{in}(t) = e_{out}(t)\ ,\ \ f_{in}(t) = f_{out}(t)$ (8)

Transducer, TD: $e_{in}(t) = f_{out}(t)\ ,\ \ f_{in}(t) = e_{out}(t)$ (9)

Table 3 Qualitative operations

[X]+[Y]

[Y] \ [X]	--	-	0	+	++
++	0	+	++	++	++
+	-	0	+	+	++
0	--	-	0	+	++
-	--	-	-	0	d
--	--	--	--	-	0

[X]-[Y]

[Y] \ [X]	--	-	0	+	++
++	--	--	--	-	d
+	--	-	-	0	+
0	--	-	0	+	++
-	-	0	+	+	++
--	0	+	++	++	++

[X]x[Y]

[Y] \ [X]	--	-	0	+	++
++	--	--	d	++	++
+	--	-	0	+	++
0	0	0	0	0	d
-	++	+	0	-	--
--	++	++	0	--	--

[X]/[Y]

[Y] \ [X]	--	-	0	+	++
++	-	-	0	+	+
+	-	-	0	+	+
0	/	/	/	/	/
-	+	+	0	-	-
--	+	+	0	-	-

- for elements of 0-junction and 1-junction

  0-junction: the efforts on the bonds attached to a 0-junction are all equal and the algebraic sum of the flows is zero, $\sum f = 0$;

  1-junction: the flows on the bonds attached to a 1-junction are all equal and the algebraic sum of the efforts is zero, $\sum e = 0$.

For a building construct at any 0-junction or 1-junction, there are two qualitative equations representing relationships of efforts and flows respectively as well as qualitative equations for each connected terminal.

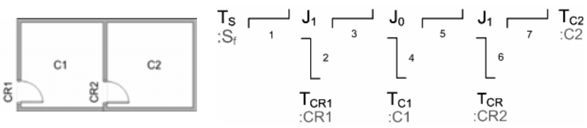
Example of QABGs for space-people system

Figure 2 is a simple space-people system with two rooms (space-capacitors C1 and C2) and two doors (controllers CR1 and CR2). People move from the outside, source S, into this plan arrangement. The construction of an ABG/a QABG for this space-people system including a graphical representation and mathematical equations is as follows:

- S, C1, C2, CR1, and CR2 are one-port ABG elements. Associated with a bond, they can be either linked to a 0 or 1 spatial junction. C1 associated with bond 4 is linked to a 0-junction. C2 associated with bond 7 is linked to a 1-junction. People move into room C1, they can further move into room C2 different from the place where they move from. People move into room C2, they cannot move to other rooms except the room where they moved from. Eqs. (15) and (19) represent people-flow variations within rooms C1 and C2. Further, people-changes of C1 and C2 can be obtained from the time integration of *f*4 and *f*7.
- People move from the outside, source S, through door CR1 into room C1. S and CR1 are associated with bonds 1 and 2 respectively. Both are linked to a 1-junction, on the left hand side of Figure 2(b). Then, from room C1 through door CR2, people can move to room C2. CR2 associated with bond 6 and C2 associated with bond 7 are linked to a 1-junction, on the right hand side of Figure 2(b). 1-junction located on the left hand side associated with bond 3 and 1-junction located on the right hand side associated with bond 5 link to the 0-junction.

  Eqs. (10) and (11) show power relations occurring at 1-junction linked with bonds 1, 2, and 3; Eqs. (13) and (14) show power relations occurring at 0-junction linked with bonds 3, 4, and 5; and Eqs. (16) and (17) show power relations occurring at 1-junction linked with bonds 5, 6, and 7. Eqs. (12) and (18) show unit people-energy dissipated at places of Doors CR1 and CR2.

To model a QABG graphical representation for this space-people system, simply replace ABG elements and bonds by QABG elements and bicausal bonds, Figure 2(b).



(a) (b)

Figure 2 A simple space-people system (a) drawing and (b) QABG

$$e1(nT) = e2(nT) + e3(nT) \quad (10)$$

$$f1(nT) = f2(nT) = f3(nT) \quad (11)$$

$$e2(nT) = CR1 \times f2(nT) \quad (12)$$

$$e3(nT) = e4(nT) = e5(nT) \quad (13)$$

$$f3(nT) = f4(nT) + f5(nT) \quad (14)$$

$$f4(nT) = C1 \times (e4(nT) - e4((n-1)T)) \quad (15)$$

$$e5(nT) = e6(nT) + e7(nT) \quad (16)$$

$$f5(nT) = f6(nT) = f7(nT) \quad (17)$$

$$e6(nT) = CR2 \times f6(nT) \quad (18)$$

$$f7(nT) = C2 \times (e7(nT) - e7((n-1)T)) \quad (19)$$

APPLICATION OF QABGS

An application of QABGs for a building construct of a space-people system is presented. A simple floor plan with a corridor and three rooms is used as an example. Figure 3(a) is the plan drawing. Figures 3(b) and Figure 3(c) are the ABG and the QABG respectively. Qualitative equations of this space-people system are in Table 4, Eqs. (20) to (40).

The direction of people moving from the outside into different rooms within a building is used in this example but not people moving out of rooms. The simulations and inferences of people behaviours and people-energy variations commence from applying qualitative values of normal and abnormal behaviours to power variable of people, i.e. effort and flow, and elements, e.g. I, C, R, and CR, in the qualitative equations. Then the dependant variables among the qualitative equations are evaluated sequentially to obtain the result of people-energy variation.

Five preliminary types of behaviours of people and the variations of people-energy for this space-people system are modelled. People move from the outside into this spatial arrangement. They move via the corridor into the room(s). They can move into one room, Cases A and B, Figures 4(a) and 4(b); into two rooms where they have access to each other, Case C,

Figure 4(c); into two rooms where they have no access to each other, Case D, Figures 4(d); or into these three rooms, Case E, Figure 3. Controllers, CR, i.e. doors, control movements of people. Cases A, B, and C can be viewed as SISO systems (single input and single output), and Cases D and E as SIMO systems (single input and multiple outputs).

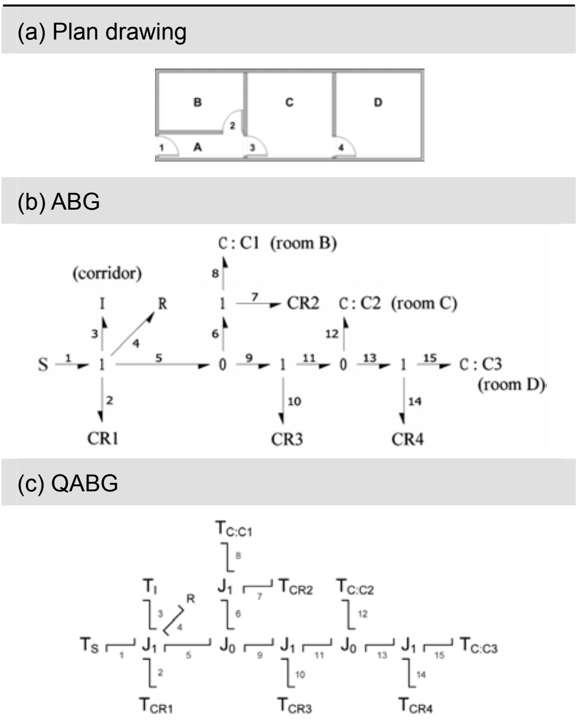


Figure 3 Case for simulation of people behaviour and people-energy variation (Case E)

Details of simulation and inference of people behaviours and people-energy variations of Case E, Table 4, where CR1 to CR4 are all open, are as follows

- Assign normal values, [+], to all component parameters in qualitative equations of this system.

  People move from the source, S, the outside, through the door, CR1, via the corridor into different rooms. They move in the normal velocity. Therefore, the qualitative values of all people-flows, *f*, within the system are all [+].

  Rooms B, C, and D contain people. They remain stable/normal. Qualitative values of C1, C2, and C3 are all [+].

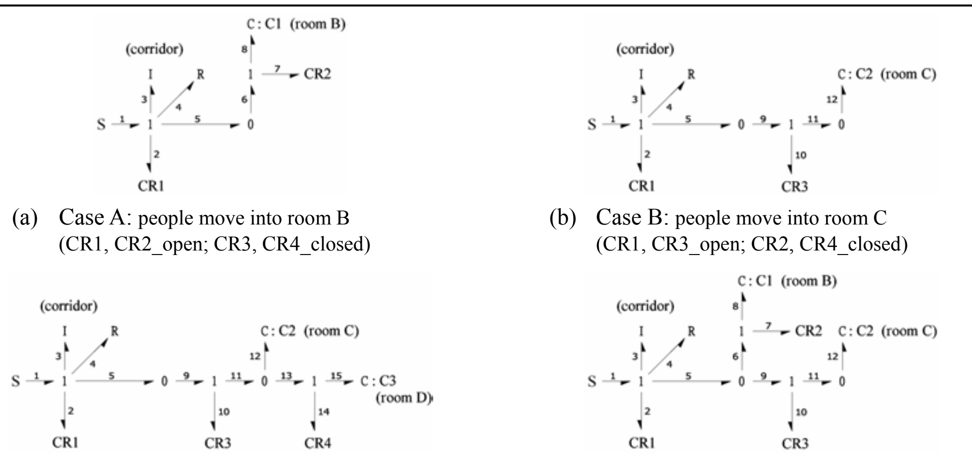
  Corridor, I, stores people-impulse, and space-resistor, R, consumes people-energy, these behaviours remain stable/normal. That is, both their qualitative values are [+].

- In the first inference, since doors, CR1 to CR4, are all open, these qualitative values are all [0] that leads the qualitative values of *e*2, *e*7, *e*10, and *e*14 to [0], Eqs. (22), (29), (33), and (39).

  Qualitative values of all people-flows as well as of I and R are [+]. Thus, the qualitative values of *e*3 and *e*4 are obtained as [0] and [+] respectively, Eqs. (23) and (24).

  From the corridor, people can move through door CR2 to room B and/or through door CR3 to room C, where there is no access to each other, Eqs. (25) and (26). People moving into room C, they can stay in this room or move through door CR4 to room D, Eqs. (34) and (35).

  People moving into different rooms, the qualitative



(a) Case A: people move into room B (CR1, CR2_open; CR3, CR4_closed)

(b) Case B: people move into room C (CR1, CR3_open; CR2, CR4_closed)

(c) Case C: people move into rooms C and D (CR1, CR3, CR4_open; CR2_closed)

(d) Case D: people move into rooms B and C (CR1, CR2, CR3_open; CR4_closed)

Figure 4 ABGs for Cases A, B, C, and D value of unit people-energy variation moving into a room is equal to the sum of unit people-energy varied around a door and in a room, Eqs. (27), (31) and (37). Since unit people-energy variations within rooms B, C, and D at time *nT* are uncertain and depend on the current condition, thus qualitative values of *e*8, *e*12, and *e*15 are all dependant values, [d], Eqs. (30), (36), and (40). In addition, the qualitative values of *e*13, *e*11, *e*9, *e*6, *e*5, and *e*1 are dependant values, [d], as well, Eqs. (37), (34), (31), (27), (25) and (20).

- The second inference is to infer the qualitative values of unit people-energy variations of *e*8, *e*12, and *e*15, the output of this space-people system.

  The qualitative value of *e*8 at time ((*n-1*)*T*) can be either [0] or [+], so can be *e*12, and *e*15. That is, the variation of people-energy can be zero or stable/normal. We apply qualitative value of [+] at time ((*n-1*)*T*) to *e*8, *e*12, and *e*15.

  At the moment of people moving into room B, the people-energy variation within the room is increased suddenly compared with the previous normal/stable status within the room. It is unstable/abnormal. Assume, people move into the room during the period between ((*n-1*)*T*) and *nT*. Thus, the qualitative value of *e*8 during the period between ((*n-1*)*T*) and *nT* is [++]. It is equal to the qualitative values of people-energy variations caused by people moving into rooms C and D, $e8(nT)=e12(nT)=e15(nT)=[++]$. Therefore, qualitative values of *e*13, *e*11, *e*9, *e*6, *e*5, and *e*1 are obtained as [++].

The direction of people moving from the outside into a building then into different rooms within this building is discussed in this paper. The movement of people in the opposite direction is not included. Figure 5 shows the result of simulation and inference of people behaviours and people-energy variations during the time period nT in rooms B, C, and D including people-flow, unit people-energy, people-change, and people-energy, Figures 5(a) to 5(d).

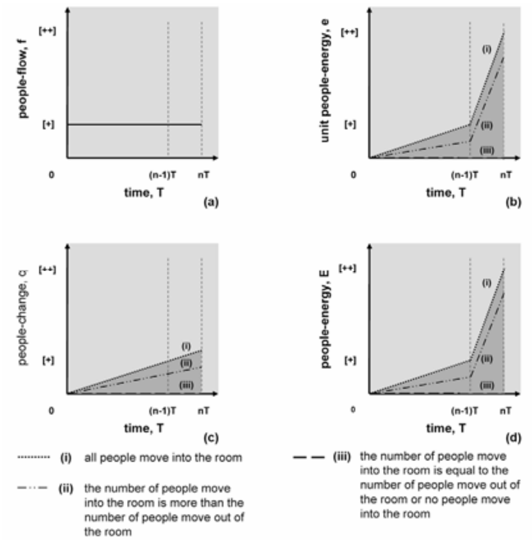


Figure 5 People behaviour and people-energy variation (*a*) *people-flow,* (*b*) *unit people-energy,* (*c*) *people-change, and* (*d*) *people-energy*

Table 4 Simulations of people behaviour and energy variation in Case E

Qualitative Equations		First inference	Second inference
$e1(nT)=e2(nT)+e3(nT)+e4(nT)+e5(nT)$	(20)	$[d]=[0]+[0]+[+]+[d]$	$[++]=[0]+[0]+[+]+[++]$
$f1(nT)=f2(nT)=f3(nT)=f4(nT)=f5(nT)$	(21)	$[+]=[+]=[+]=[+]=[+]$	
$e2(nT)=CR1\times f2(nT)$	(22)	$[0]=[0]\times[+]$	
$e3(nT)=I\times(f3(nT)-f3((n-1)T))$	(23)	$[0]=[+]\times([+]-[+])$	
$e4(nT)=R\times f4(nT)$	(24)	$[+]=[+]\times[+]$	
$e5(nT)=e6(nT)=e9(nT)$	(25)	$[d]=[d]=[d]$	$[++]=[++]=[++]$
$f5(nT)=f6(nT)+f9(nT)$	(26)	$[+]=[+]+[+]$	
$e6(nT)=e7(nT)+e8(nT)$	(27)	$[d]=[0]+[d]$	$[++]=[0]+[++]$
$f6(nT)=f7(nT)=f8(nT)$	(28)	$[+]=[+]=[+]$	
$e7(nT)=CR2\times f7(nT)$	(29)	$[0]=[0]\times[+]$	
$f8(nT)=C1\times(e8(nT)-e8((n-1)T))$	(30)	$[+]=[+]\times([d]-[+])$	$[+]=[+]\times([++]-[+])$
$e9(nT)=e10(nT)+e11(nT)$	(31)	$[d]=[0]+[d]$	$[++]=[0]+[++]$
$f9(nT)=f10(nT)=f11(nT)$	(32)	$[+]=[+]=[+]$	
$e10(nT)=CR3\times f10(nT)$	(33)	$[0]=[0]\times[+]$	
$e11(nT)=e12(nT)=e13(nT)$	(34)	$[d]=[d]=[d]$	$[++]=[++]=[++]$
$f11(nT)=f12(nT)+f13(nT)$	(35)	$[+]=[+]+[+]$	
$f12(nT)=C2\times(e12(nT)-e12((n-1)T))$	(36)	$[+]=[+]\times([d]-[+])$	$[+]=[+]\times([++]-[+])$
$e13(nT)=e14(nT)+e15(nT)$	(37)	$[d]=[0]+[d]$	$[++]=[0]+[++]$
$f13(nT)=f14(nT)=f15(nT)$	(38)	$[+]=[+]=[+]$	
$e14(nT)=CR4\times f14(nT)$	(39)	$[0]=[0]\times[+]$	
$f15(nT)=C3\times(e15(nT)-e15((n-1)T))$	(40)	$[+]=[+]\times([d]-[+])$	$[+]=[+]\times([++]-[+])$

People move in one direction and in normal velocity, Figure 5(a). Line (i) in Figures 5(b) to 5(d) is the result for rooms B and D. People move into these rooms but not out of the rooms. In contrast, people move into room C, they can stay or move out of the room into room D. The simulation and inference result for room C can be Lines (i), (iii), or in-between Lines (i) and (iii). Since the number of people moving into room C is always greater than, Line (i) or in-between Lines (i) and (iii), or equal to the number of people moving out of the room, Line (iii).

CONCLUSION AND FUTURE WORK

The result shows that QABGs for space-people system can be applied in the conceptual design stage to represent the static and dynamic aspects, that is, spatial arrangement as well as people behaviours and people-energy variations, concurrently without the need of complete design knowledge of building constructs. QABG application for space-people system can be used to simulate people-flow, unit people-energy, people-change, and people-energy of a room within the system when time varies.

QABGs can also be applied in different building energy systems to represent structures of different building energy systems and behaviours of building energy moving in these structures. The application of QABGs has the potential for representing the interactions between different building constructs. By arranging different building constructs in interconnected different layers, when one component of any building construct is changed, components in the related layer(s) will be changed. This will be developed in future research.

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