Qualitative Approach to an Energy-based Unified Representation for Building Design

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Archi Bond Graphs (ABGs) that have been developed as an energy-based unified representation for building design can be applied for the static and dynamic aspects of buildings. This paper presents simulations of people behaviour and people-energy variation as well as building energy flow and variation by qualitative Archi Bond Graphs (QABGs).

Keywords: Archi Bond Graphs, building design, energy-based representation, qualitative approach.

1 INTRODUCTION

Representations enable designers to establish frameworks to develop their designs and also provide foundations for designers to evaluate their designs. A building can be viewed as a system that consists of a wide range of building constructs, such as spatial arrangement, circulation arrangement, and building energy arrangements, including electricity, hydraulics, HVAC, and lighting energy. When designers develop a building design project, different representations are used for different building constructs. The majority of current representations are employed in the intermediate and final stages of design. We develop an energy-based unified representation for building design called Archi Bond Graphs (ABGs) (Gero and Tsai 2004; 2005). ABGs can be applied in the conceptual as well as the intermediate and final design stages. They can represent the structures of different building constructs as well as behaviours of people and building energy flow within these building constructs.

Qualitative reasoning is critical for comprehending the problem in the first place, formulating a plan for solving the problem, identifying which quantitative laws apply to the problem, and interpreting the results of quantitative analysis. 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 (Williams 1991; de Kleer 1993; Werthner 1994; Wang and Linkens 1996). Qualitative Archi Bond Graphs (QABGs) are based on discrete symbols by replacing numerical constants with symbol names that correspond to human knowledge and provide a more general model, applicable to a wide range of different conditions in building design.

This paper commences with the brief introduction of the development of a unified representation for building design, from regular bond graphs (RBGs) and bond graphs for multiple domains (MBGs) to ABGs and QABGs. It then depicts the representations of QABGs for people behaviour associated with people-energy variation and building energy flow associated with building energy variation. An application of QABGs is presented to simulate people behaviour and people-energy variation within a space-people system as well as electrical energy flow and variation within a lighting system.

2 RBGS, MBGS, AND ABGS

Bond graphs introduced by Paynter (Paynter 1961; Karnopp et al. 2000), called regular bond graphs (RBGs) in our research, are a unified approach to the modelling and analysis of the dynamics of hybrid multi-domain systems. They combine a systematic graphical representation with mathematical equations and consist of variables, elements, constitutive relations, and causality. As a modelling tool, RBGs can be used in the conceptual design stages. Based on RBGs we develop more general bond graphs for multiple domains (MBGs). Within MBGs, energy, E, and displacement, q, are defined in a broad and general sense as the ability and/or power to do or achieve something and as the change caused by energy respectively. Based on that, other variables and elements of MBGs are defined (Gero and Tsai 2004; 2005).

ABGs focusing on the domain of architecture can be applied to space-people systems and building energy systems. Power variables, effort and flow, are defined in ABGs as the average amount of energy needed for a unit of change and the number of changes in a unit of time respectively. In ABGs for disparate 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 are defined in Table 1(a). ABG elements can be categorized into 1-port and multi-port elements. 1-port elements are source (S), i.e. source of effort (Se) and source of flow (Sf), inducer (I), capacitor (C), resistor (R), controller (CR), meter (M), and building construction/component (B), i.e. exterior building construction/component (Be) and interior building construction/component (Bi). Multi-port elements include transformer (TF), transducer (TD), 0-junction, and 1-junction. 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 are defined in Table 1(b) (Gero and Tsai 2004; 2005).

Table1. (a) ABG variables and (b) ABG elements for space-people system (Gero and Tsai 2005)

(a) ABG variables for space-people system	
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

(b) 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

Causality in bond graphs establishes the cause and effect relationships between the factors of power. ABG's bicausal bond, extending from the bicausal bond introduced by Gawthrop (1995), has two pairs of power variables attached to a bond. It has the capacity to represent energy-flow moving back and forth associated with energy variations (Gero and Tsai 2005).

3 QABGs

Grounded on ABGs, QABGs associate graphical representation with qualitative equations. A QABG graphical representation consists of elements and element-link-relationships. ABG elements and linking bonds represent nodes and arcs in QABGs. Nodes can be terminals (T) or junctions (J). Terminals include energy source and energy operators, i.e. inductor, capacitor, resistor, controller, meter, and building construction/component. Junctions include transformer, transducer, 0-junction, and 1-junction. An arc has two pairs of power variables: effort (e) and flow (f). 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 equations of ABGs associated with qualitative values and qualitative operations provide a mechanism for reasoning about energy transfer and transformation within the system. 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 the qualitative operation under different conditions. Extending the qualitative values of variables for RBGs discussed (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 DR elements, [+] denotes the normal behaviour;
- R and DR elements, [++] denotes element blocked, and [0] denotes element leakage or short circuit.

Qualitative operations in QABGs include addition, substraction, multiplication, division, and equal: {+, -, ×, ÷, =}.

QABGs qualitative equations represent constitutive relations for the system structure as well as people behaviours, building energy flows, and variations of people-energy and building energy

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

  $e = R \times f$, $f = C\frac{d}{dt}e$, and $e = I\frac{d}{dt}f$ (1)

- for elements of I, C, R, and CR, t is a sampling time period, where $t_2 > t_1$

  Inductor, I: $e(t_2) = I \times (f(t_2) - f(t_1))$ (2)

  Capacitor, C: $f(t_2) = C \times (e(t_2) - e(t_1))$ (3)

  Resistor, R: $e(t) = R \times f(t)$ (4)

  Controller, CR: $e(t) = R \times f(t)$ (5)

- for elements of TF and TD

  Transformer, TF: $e_{in}(t) = e_{out}(t)$, $f_{in}(t) = f_{out}(t)$ (6)

  Transducer, TD: $e_{in}(t) = f_{out}(t)$, $f_{in}(t) = e_{out}(t)$ (7)

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

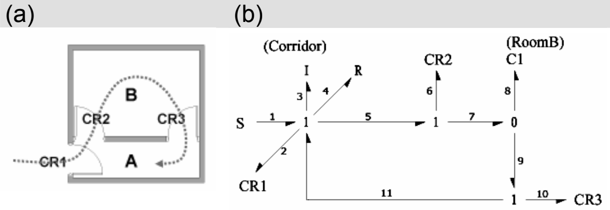
4 People Behaviour and People-energy Variation as well as Building Energy Flow and Building Energy Variation

QABGs can be applied to simulate people behaviour and people-energy variation within a space-people system as well as building energy flows and building energy variations within building energy systems. The difference between people-flow moving within a space-people system and building energy flow moving within a building energy system is that people-flow can move in the opposite direction of people-flow moving from the outside into a building then into different rooms but building energy flow is always unidirectional.

The following two cases show that people move from the outside through the door, CR1, into a building via a corridor, I, and then through the door CR2 into Room B. Further, they move through a different door, CR3, or through the same door, CR2, out of the room.

Case A, people within this building move from the corridor, I, through the door, CR2, into Room B. Further, they move through another door, CR3, out of this room and back to the corridor. Fig. 1 shows the plan drawing with people-flow, the ABG, and equations of effort and flow relationships in this case. People move in one direction from the outside and then within this building. The movements of people-flows within this system are normal. The qualitative value of each people-flow is equal. The variations of people-energy caused by people moving from the outside into this building, $e1(nT)$, and moving out of Room B, $e11(nT)$, are the inputs of 1-junction linked by Bonds 1, 2, 3, 4, 5, and 11. At this 1-junction, the sum of people-energy inputs, $e1(nT)$ and $e11(nT)$, is equal to the sum of people-energy outputs, $e2(nT)$, $e3(nT)$, $e4(nT)$, and $e5(nT)$.

(a) (b) (c)



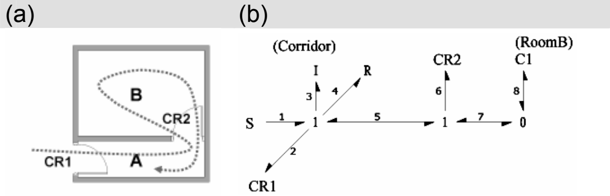
$$e1(nT) + e11(nT) = e2(nT) + e3(nT) + e4(nT) + e5(nT) \quad (8)$$

$$f1(nT) = f11(nT) = f2(nT) = f3(nT) = f4(nT) = f5(nT) \quad (9)$$

Fig. 1. Case A (a) plan drawing and people flow, (b) ABG, and (c) equations of relationships of effort and flow

Case B, people within this building move from the corridor, I, through the door, CR2, into Room B. Further, they move through the same door, CR2, out of this room and back to the corridor. Fig. 2 shows the plan drawing with people-flow, the ABG, and equations of effort and flow relationships in this case. Similar to Case A, the movements of people-flows within this system are normal and the qualitative value of all people-flows moving from the outside and then within this building are equal. However, people moving out of Room B is opposite to the direction of people moving from the outside into the building and then into rooms within this building. Therefore the qualitative operator of people-flow out of Room B is substraction, -, and the qualitative value is [-]. The people-energy variations of people moving from the outside into this building, $e1(nT)$, is the only input of 1-junction linked by Bonds 1, 2, 3, 4, and 5. The input, $e1(nT)$, is equal to the sum of people-energy outputs, $e2(nT)$, $e3(nT)$, $e4(nT)$, and $e5(nT)$, as well as the people-energy variation caused by people-flow moving through door CR2 out of Room B and into the corridor, $e5'(nT)$. The qualitative operation of $e5'(nT)$ is substraction, -, and its qualitative value is [--] revealing that people-energy in Room B is decreased. In addition, the people-energy in the corridor is increased that is caused by people-flow moving out of Room B and back into the corridor.

(a) (b) (c)

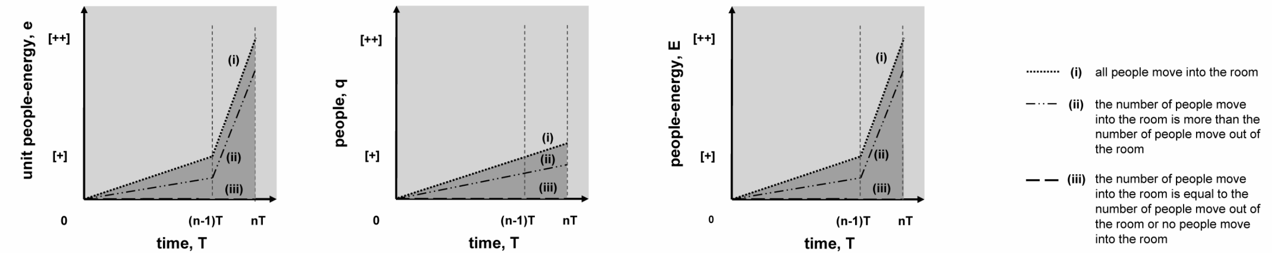


$$e1(nT) = e2(nT) + e3(nT) + e4(nT) + (e5(nT) - e5'(nT)) \quad (10)$$

$$f1(nT) = f2(nT) = f3(nT) = f4(nT) = f5(nT) = -f5'(nT) \quad (11)$$

Fig. 2. Case B (a) plan drawing and people flow, (b) ABG, and (c) equations of relationships of effort and flow

Fig. 3 shows people behaviour and energy variations within the space-people system during the time period of nT, where T is a sampling time period. Within Figs. 3(a) to 3(c), (i) denotes all people moving into the room and (iii) denotes the number of people moving into the room is equal to the number of people moving out of the room or there is no people movement. The area inbetween (i) and (iii), for instance (ii), represents that the number of people moving into the room is more than the number of people moving out of the room. The number of people moving out of a room can be equal or less than the number of people moving into the room.



(a) (b) (c)

Fig. 3. People behaviour and energy variation (a) unit people-energy, (b) people, and (c) people-energy

5 SIMULATION OF QABGS

The spatial arrangement and lighting system of a building with a corridor and three rooms are used as examples to show QABG simulations of people behaviour and people-energy variation within a space-people system and building energy flow and variation within a building energy system. Fig. 4(a) shows the drawing of the floor plan with people moving in it. People move from the outside through door CR1 into the building to the corridor. Form the corridor, they move through door DR2 into Room B, move through door CR3 into Room C and then through the same door CR3 out of the room, and move through door CR4 into Room D and then through door CR5 out of this room. Fig. 4(b) is the ABG and Table 1 is the qualitative equations and simulation of people behaviour and energy variation. Fig. 5(a) shows the drawing of the lighting system of this building and Fig. 5(b) is the ABG. The formulation of qualitative equations as well as the simulation of electrical energy flows and energy variations are similar to those in the space-people system but not illustrated in details here.

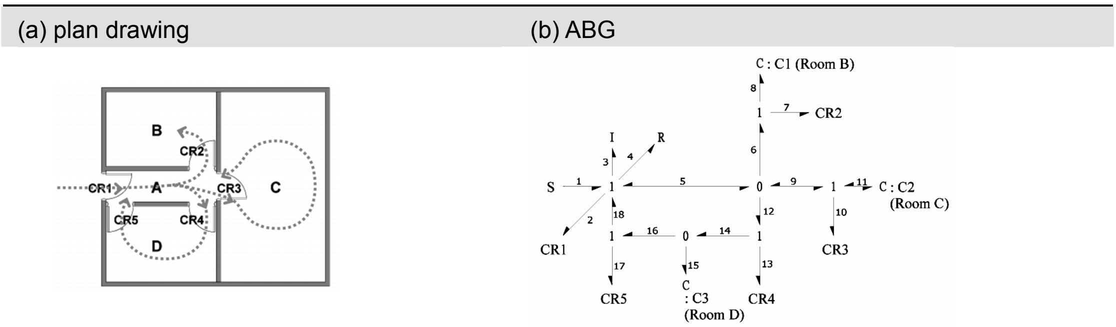


Fig. 4. People move into a room and the energy variation (a) people-flow, (b) unit people-energy, (c) people, and (d) people-energy

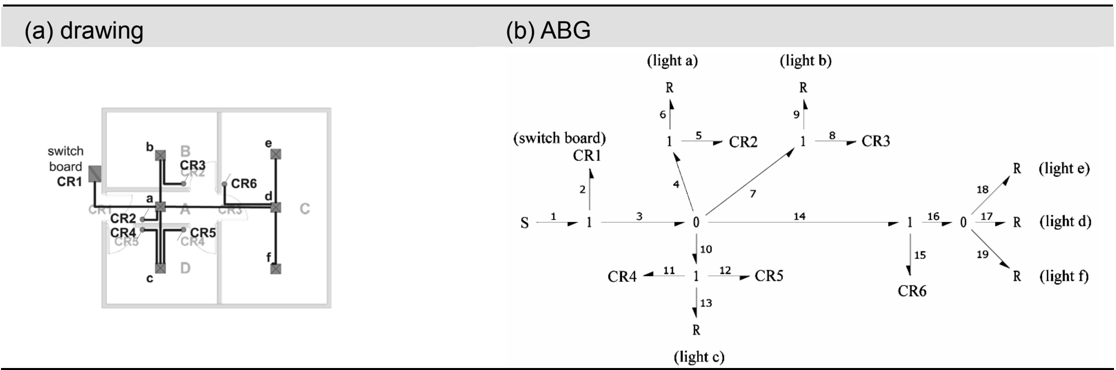


Fig. 5. Lighting system (a) drawing, and (b) ABG

6 CONCLUSION AND FUTURE WORK

The result shows QABGs can be applied in the conceptual design stage to represent the static and dynamic aspects of building without the need for complete design knowledge of building constructs. Graphical representations and qualitative equations of QABGs have the capacities to represent and simulate different people behaviours and people-energy variations within the people-space system as well as building energy flows and energy variations within building systems. The application of QABGs also has the potential to represent and simulate energy interactions between different building constructs. It will be developed in future research.

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Table 1. Qualitative equations and simulation of people behaviour and energy variation

Qualitative equations of people behaviours		First inference	Second inference	Third inference
$e1(nT)+e18(nT)=e2(nT)+e3(nT)+e4(nT)+(e5(nT)-e5'(nT))$	(12)	$[d]+[d]=[0]+[0]+[+]+[d]$	$[++]+[++]=[0]+[0]+[+]+[++]$	$[++]+[++]=[0]+[0]+[+]+([++]-[--])$
$f1(nT)=f18(nT)=f2(nT)=f3(nT)=f4(nT)=f5(nT)=-f5'(nT)$	(13)	$[+]=[+]=[+]=[+]=[+]=[+]=[+]$	$[+]=[+]=[+]+[+]=[+]=[+]=(-[-])$	
$e2(nT)=CR1\times f2(nT)$	(14)	$[0]=[0]\times[+]$		
$e3(nT)=I\times(f3(nT)-f3((n-1)T))$	(15)	$[0]=[+]\times([+]-[+])$		
$e4(nT)=R\times f4(nT)$	(16)	$[+]=[+]\times[+]$		
$(e5(nT)-e5'(nT))=e6(nT)=(e9(nT)-e9'(nT))=e12(nT)$	(17)	$[d]=[d]=[d]=[d]$	$[++]=[++]=[++]=[++]$	$([++]-[--])=[++]=([++]-[--])=[++]$
$(f5(nT)-f5'(nT))=f6(nT)+(f9(nT)-f9'(nT))+f12(nT)$	(18)	$[+]=[+]+[+]+[+]$	$([+]-[-])=[+]+([+]-[-])+[+]$	
$e6(nT)=e7(nT)+e8(nT)$	(19)	$[d]=[0]+[d]$	$[++]=[0]+[++]$	
$f6(nT)=f7(nT)=f8(nT)$	(20)	$[+]=[+]=[+]$		
$e7(nT)=CR2\times f7(nT)$	(21)	$[0]=[0]\times[+]$		
$f8(nT)=C1\times(e8(nT)-e8((n-1)T))$	(22)	$[+]=[+]\times([d]-[+])$	$[+]=[+]\times([++]-[+])$	
$(e9(nT)-e9'(nT))=(e10(nT)+e10'(nT))+(e11(nT)-e11'(nT))$	(23)	$[d]=[0]+[d]$	$[++]=[0]+[++]$	$([++]-[--])=[0]+([++]-[--])$
$(f9(nT)-f9'(nT))=(f10(nT)-f10'(nT))=(f11(nT)-f11'(nT))$	(24)	$[+]=[+]=[+]$	$([+]-[-])=([+]-[-])=([+]-[-])$	
$e10(nT)=CR3\times f10(nT)$	(25)	$[0]=[0]\times[+]$		
$e10'(nT)=CR3\times f10'(nT)$	(26)	$[0]=[0]\times[-]$		
$f11(nT)=C2\times(e11(nT)-e11((n-1)T))$	(27)	$[+]=[+]\times([d]-[+])$	$[+]=[+]\times([++]-[+])$	
$f11'(nT)=C2\times(e11'(nT)-e11'((n-1)T))$	(28)	$[-]=[+]\times([d]-[-])$	$[-]=[+]\times([--]-[-])$	
$e12(nT)=e13(nT)+e14(nT)$	(29)	$[d]=[0]+[d]$	$[++]=[0]+[++]$	
$f12(nT)=f13(nT)=f14(nT)$	(30)	$[+]=[+]=[+]$		
$e13(nT)=CR4\times f13(nT)$	(31)	$[0]=[0]\times[+]$		
$e14(nT)=e15(nT)=e16(nT)$	(32)	$[d]=[d]=[d]$	$[++]=[++]=[++]$	
$f14(nT)=f15(nT)+f16(nT)$	(33)	$[+]=[+]+[+]$		
$f15(nT)=C3\times(e15(nT)-e15((n-1)T))$	(34)	$[+]=[+]\times([d]-[+])$	$[+]=[+]\times([++]-[+])$	
$e16(nT)=e17(nT)+e18(nT)$	(35)	$[d]=[0]+[d]$	$[++]=[0]+[++]$	
$f16(nT)=f17(nT)=f18(nT)$	(36)	$[+]=[+]=[+]$		
$e17(nT)=CR5\times f17(nT)$	(37)	$[0]=[0]\times[+]$		