APPLICATION OF BOND GRAPH MODELS TO THE REPRESENTATION OF BUILDINGS AND THEIR USE

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Abstract. This paper presents some early research on developing a representation for buildings that has the capacity to integrate a number of disparate design domains. This representation is developed based on bond graphs. Its goal is to represent not only steady state topologies of spaces in buildings, but also building dynamics, people and other flows within those spaces.

1. Introduction

There are several mature representations for the final stage of building design in CAD systems. However, representations for the conceptual stage of design are still developing. They primarily focus on representing the steady state of buildings such as spatial relationships or topologies. The main purpose of constructing buildings is for people and/or for goods production or storage. Building dynamics, which includes people flow, goods flow and energy flow, is not included in the representations of this kind. There is a need to develop a representation which could simultaneously represent the three major aspects of buildings: the building as a collection of objects, the building as a container for people and their goods and the building as a container and transformer of processes.

We consider a building as a system that can initially be modelled qualitatively to determine its behaviour. Then, by assigning numerical parameters, we can generate a quantitative model for various purposes. Bond graphs, which have been applied in conceptual design in engineering fields, have the potential to allow for this mixing of qualitative and quantitative features in a single representation. They also provide some desirable systemic features which are suitable as a foundation for the development of a new presentation.

This paper commences with an overview of bond graphs including their background, characteristics, concepts, elements, variables and constitutive relations. Three tasks of developing bond graphs for buildings and their use are outlined. This is followed by the beginnings of the development of bond graphs which can be applied in multiple domains, and then the development of bond graphs which can be applied in the domain of architecture will be discussed.

2. System Representations

A system can be represented by drawings, graphs, bond graphs, block diagrams and equations (Thoma, 1990). System representations become more abstract from drawings to equations, Figure 1.

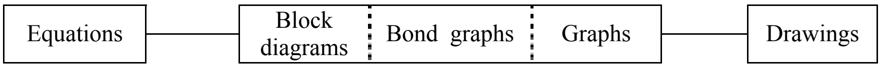


Figure 1. System representations (after Thoma 1990).

Graphs can be analogized as circuits for system representations in engineering. Circuits are composed of element and circuit symbols which are more or less simplified or stylized pictures of the real components. Thoma (1975) lists the drawbacks of graphs as: (1) the equivalent circuit might lose its similarity with the real layout due to fictitious elements; (2) whether each symbol is a real component or an idealized element must be indicated separately; and (3) new symbols must be learned for each discipline.

A block diagram is the basic tool of control engineering. It is a causal representation (Thoma and Karnopp 1973), giving a network of causes and effects represented by blocks and connections. The signal flow graphs of control engineering are a related but not so useful representation in the case of non-linear systems. Two drawbacks of block diagrams listed by Thoma (1975) are: (1) a return action between components in block diagrams must always be shown as a separate feedback connection, whilst in reality the components have only one connection such as electrical wires or pipes; and (2) block diagrams for a given technical system can have a radically different appearance because of the different possible causalities.

3. Bond Graphs

3.1. INTRODUCTION TO BOND GRAPHS

Bond graphs introduced by Henry Paynter in 1961 (Thoma 1975; Thoma 1990; Gawthrop and Smith 1996; Karnopp, Margolis, and Rosenberg 2000) are a kind of graphical language and systematic representation. They include elements and constitutive relations which can be used to express the common energy transfer or transform behaviour underlying the several physical domains of mechatronic systems in a uniform notation. In the beginning, they were applied in physical multidisciplines, such as mechanics, electronics and hydraulics, and then in the domain of economics. The characteristics of bond graphs include:

- being able to reveal the relationships among system, subsystems, and elements;
- being able to obtain important qualitative physical information as a conceptual model;
- not only being able to represent the topology of subsystems or elements of different physical domains, but also being able to represent the relationships of their products among them;
- being able to represent dynamic systems; and
- being flexible and extendable.

The application of bond graphs within a system representation shown in Figure 1 implies that drawings can be converted into graphs and then bond graphs. The bond graph itself also embodies equations.

3.2. THE CONCEPT OF BOND GRAPHS

The concepts of bond graphs include port and bond, elements, variables, constitutive relations and causality.

Figure 2 shows the concept of the basic bond graph component. Between two elements, there is always a bond. Every bond has two power variables, a pair of conjugated variables, one is effort (*e*), and the other is flow (*f*) associated with it. Energy will flow through the bond in either direction. Ports are the places where energy transfer happens or occurs. They are also the contact points of sub-systems.

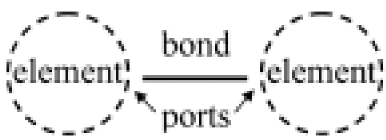
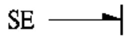
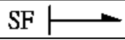
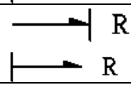
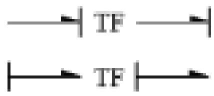
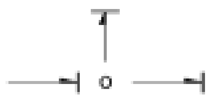
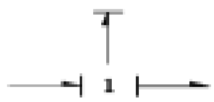


Figure 2. Bond and ports of bond graph.

Bond graphs consist of nine types of elements, they are source of effort (Se), source of flow (Sf), inductor (I), capacitor (C), resistor (R), transformer (TF), gyrator (GY), 0-junction and 1-junction. These labels are derived from mechatronic systems but do not refer to those classes of elements in other systems. These elements can be divided into three categories: one-port element, two-port element and three or multi-port element. Table 1 shows elements of bond graphs and their symbols.

TABLE 1. Elements of bond graphs.

Element		Symbol
One-port Element (Active)	Se, source of effort	
	Sf, source of flow	
One-port Element (Passive)	I-element	
	C-element	
	R-element	 or
Two-port Element	TF, transformer	 or
	GY, gyrator	 or
Three-port Element (Multi-port element)	0-junction	ex 
	1-junction	ex 

(1) One-port elements include active elements, which give reaction to the source, and passive elements, which are idealized elements because they contain no sources of power. Se and Sf are active one-port elements, representing source of effort and source of flow respectively. I, C and R elements are passive one-port elements representing inductor, capacitor and resister respectively. I-element and C-element are energy storage elements, the former stores *p*-variable (e.g. momentum), the later stores *q*-variable (e.g. displacement). Usually, R-element dissipates energy.

(2) Two-port elements are TF and GY. TF is transformer, which does not create, store or dissipate energy. It conserves power and transmits the

factors of power with power scaling as defined by the transformer modulus. GY is gyrator, which are used in most of the cases where power from one energy domain is transferred to another.

(3) Three-port or multi-port elements are 0-junction and 1-junction standing for parallel junction and serial junction respectively. 0-junction and 1-junction are also served to interconnect elements into subsystem or system models. The efforts on the bonds attached to a 0-junction are equal and the algebraic sum of the flows is zero. In contrast, the flows on the bonds attached to a 1-junction are equal and the algebraic sum of the efforts is zero.

Variables in bond graphs include effort, flow, momentum, displacement, power, and energy. The follows are variables and the constitutive relations of bond graphs (Thoma, 1975 and 1990; Karnopp, et al. 2000).

- $e(t)$ is an effort quantity, and $f(t)$ is a flow quantity. The product of effort and flow is the instantaneous power, $P(t)$, flowing between two multi-ports. In a dynamic system the effort and the flow variables, and hence the power, fluctuate in time.

$$P(t) = e(t)f(t) \tag{1}$$

- The momentum, $p(t)$, is defined as the time integral of an effort. That is

$$p(t) \equiv \int^{t} e(t)dt = p_0 + \int_{t_0}^{t} e(t)dt \tag{2}$$

- A displacement variable, $q(t)$, is the time integral of a flow variable:

$$q(t) \equiv \int^{t} f(t)dt = q_0 + \int_{t_0}^{t} f(t)dt \tag{3}$$

- The energy, $E(t)$, which has passed into or out of a port is the time integral to the power, $P(t)$. That is

$$E(t) \equiv \int^{t} P(t)dt = \int^{t} e(t)f(t)dt \tag{4}$$

Figure 3 shows relations between the variables. In addition to the constitutive relations of ‘effort and momentum’ and ‘flow and displacement’, it also implies the constitutive relations of I, C and R-element as

$$p = I \times f,\ I = \frac{p}{f};\ \ q = C \times e,\ C = \frac{q}{e};\ \ e = R \times f,\ R = \frac{e}{f} \tag{5}$$

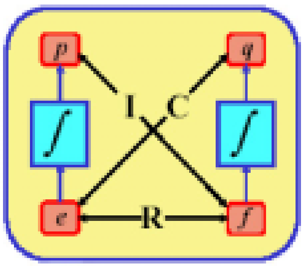


Figure 3. Relations between the variables (Cellier, 2002).

Table 2 shows examples of variables of bond graphs in the domains of mechanics, electronics, hydraulics and economics. Examples of I, C and R-element in the domains of mechanics, electronics, hydraulics and economics can be seen in Table 3.

TABLE 2. Examples of bond graph variables

Variables	Mechanics	Electronics	Hydraulics	Economics
Effort, ***e***	Force, ***F*** (N)	Voltage, ***e*** (V=N·m/C)	Pressure, $\boldsymbol{p}^a$ (N/m^2)	Unit price ($/unit)
Flow, ***f***	Velocity, ***V*** (m/s)	Current, ***i*** (A=C/s)	Volume flow rete, ***Q*** (m^3/s)	Order flow, commodity flow (unit/period)
Momentum, ***p***	Momentum, ***P*** (N·s)	Flux linkage variable, **λ** (V·s)	Pressure momentum, $\boldsymbol{p_p}$ (N·s/m^2)	Investment impulse (($/unit)·period)
Displacement, ***q***	Displacement, ***X*** (m)	Charge, ***q*** (C=A·s)	Volume, ***V*** (m^3)	Order (unit)
Power, **P**	(N·m/s)	(V·A=W =N·m/s)	(N·m/s)	Money flow ($/period)
Energy, **E**	(N·m)	(J=V·A·s =W·s=N·m	(N·m)	Money ($)

TABLE 3. I, C, R-element of bond graphs.

	Mechanics	Electronics	Hydraulics	Economics
I-element	Body (N·s^2/m)	Inductor (V·s/A)	Tube (N·s^2/m^5)	Inertia, impulse ($·period^2)/unit^2
C-element	Spring (m/N)	Capacitor (A·s/V=F: farad)	Tank (m^5/N)	Compliance Unit^2/$
R-element	Friction (N·s/m)	Resistor (V/A=Ω)	Orifice (N·s/m^5)	Demand, Supply ($·period)/unit^2

Causality establishes the cause and effect relationships between the factors of power, which are effort and flow. In each bond, the input and output are characterized by the causal stroke which is placed at the end on only one side of a bond. In Figure 4(a), effort is the output of A and flow is the output of B; in Figure 4(b), effort is the output of B and flow is the output of A. Effort and flow always move in the opposite directions. Causal stroke represents the place where flow moves away from and effort moves into.

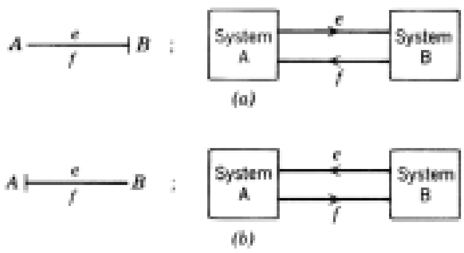


Figure 4. Causal strokes (Karnopp et al., 2000).

Figure 5(a) is an example of graphs of an electrical system; Figure 5(b) shows bond graphs of the same electrical system.

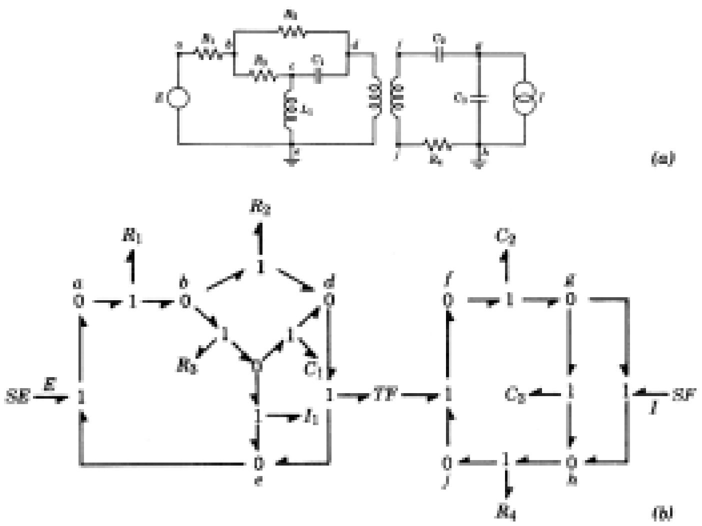


Figure 5. Causal strokes (Karnopp et al., 2000).

4. Developing Archi Bond Graphs for buildings and their use

Rivard and Fenves (2000) state that a representation for conceptual design of buildings should be able to integrate multiple views, support design evolution, favour design exploration and be extendable. Wong (2001) states that the bond graphs representation has compositionality and locality, extensibility and genericity. Therefore, it maybe suitable to investigate the possibility of using bond graphs as a foundation for the development of a representation of building and their use, called Archi Bond Graphs (ABGs).

Three tasks will be involved in the development of Archi Bond Graphs (ABGs):

Task 1: Develop bond graph representation of buildings as objects

Spaces within a building can be seen as objects. The spaces and their topological relations used to represent a building and spaces within the building might become the elements and constitutive relations of a bond graph.

Task 2: Augment the bond graph representation to include the flow of people and goods

One of the purposes in developing ABGs is to represent building dynamics. People and goods flow within buildings could be continuous or discontinuous. They are restricted to move in spaces and spatial interconnections within buildings. ABGs provide an opportunity to directly represent flows of this kind through an analogy with electric circuits, as the constitutive equations are identical.

Task 3: Augment the bond graph representation of buildings to include processes

Energy within buildings includes thermal energy, light energy, sound energy, electricity, hydraulics, conditioned air and communications. Such energy flows within building can be through walls, through space/spatial interconnections and through restricted paths, such as pipes and cables. Table 4 shows flows of energy within buildings. For instance, light energy can only flow through spaces/spatial interconnections; electricity, hydraulics and conditioned air can only flow through restricted path; thermal energy and sound energy can flow through walls and spaces/spatial interconnections; communications can flow through walls, spaces/spatial interconnections and restricted path. ABGs should have the capacity to represent topologies of these various flows and their relations with people and goods in the buildings.

TABLE 4. Flow of energy within buildings (Gero 2003).

Energy flow paths / Energy system forms	Flow through walls	Flow through spaces/spatial interconnections	Flow through restricted path
Thermal energy	○	○	
Light energy		○	
Sound energy	○	○	
Electricity			○
Hydraulics			○
Conditioned air			○
Communications inc wireless	○	○	○

5. The Development of ABGs

In order to develop ABGs, a more general bond graphs representation is needed as a basic framework. Based on the comparison of variables in the domains of physical sciences and economics and the adoption of the constitutive relations, bond graphs which could be generalized t o multiple domains, called MBGs, are developed. Within the framewor k of MBGs, ABGs are then developed.

5.1. MBGs

The development of MBGs commences from the discussion of variables of energy and displacement. Energy in different domains has different meanings, for instance, in physics its dimension could be ‘Joule ($N \cdot m$)’, in economics it could be ‘Money’. The definition of energy could be found in *Oxford Advanced Learner’s Dictionary* (2000) as

- the ability to put effort and enthusiasm into an activity, work, etc,
- the physical and mental effort that you use to do something
- a source of power, such as fuel, used for driving machines, providing heat, etc,
- the ability of matter or radiation to work because of its mass, movement, electric charge, etc.
- Displacement is the change caused by the effect of energy. As can be seen, change is displacement (length/distance) in mechanics, charge in electronics, volume in hydraulics and order in economics.
- The following are the developments and discussions of variables of MBGs:
- effort variable, *e*, is the amount of energy what is needed for a unit of change.

- flow variable, f, is the number of changes that happened in a unit of time.
- momentum variable, p, is the time integral of e, which is the amount of energy that is needed in a period of time for a unit of change.
- The displacement variable, q, is the time integral of f.
- The power variable, equals to effort variable times flow variable, is the time differential of energy
- The value of I, C and R-element and their expressions are as follows:
- I-element, I, is the unit of flow that can cause or store the amount of energy in a period of time.
- C-element, C, is the unit of effort that can cause or store the amount of changes.
- R-element, R, is the unit of flow that the amount of effort needs.
- Table 5 shows variables and I, C, R-element of MBGs.

TABLE 5. Variables and I, C, R-element of MBGs.

Effort, ***e***	$\frac{energy}{change}$
Flow, ***f***	$\frac{change}{time}$
Momentum, ***p***	$\frac{energy \cdot time}{change}$
Displacement, ***q***	$change$
Power, ***P***	$e \cdot f = \frac{energy}{change} \cdot \frac{change}{time} = \frac{energy}{time}$
Energy, ***E***	$energy$
I-element	$I = \frac{p}{f} = \frac{energy \cdot time^2}{change^2}$
C-element	$C = \frac{q}{e} = \frac{change^2}{energy}$
R-element	$R = \frac{e}{f} = \frac{energy \cdot time}{change^2}$

5.2. ABGs REPRESENTING PEOPLE FLOW WITHIN BUILDINGS

The development of ABGs commences from the discussion of variables of displacement and energy:

- Displacement, q, represents the change that occurred during a period of time. That is, the total numbers of people change within a building during a period of time.
- Energy, E, is the sum of all sub amounts of energy consumed by all sub groups of people moving within buildings. People, distance and importance are three parameters of the energy. (1) The number of people moving within a building from one space to another could be different. The more people there are the more the energy will be. (2) Distance of people moving within buildings includes horizontal distance and vertical distance. (3) Importance is a parameter which represents motivations relating to functions, purposes and activities of people moving within buildings. For instance, the amounts of energy consumed by people doing different activities, such as walking and running, will be different. People move within buildings for different purposes will consume different amounts of energy, for example, people moving in an emergency situation should consume more energy than in a relaxed situation. Functions can also affect the energy consumed by people moving within buildings. Spaces within a building could have different functions. The amount of energy consumed by people moving from Room A with function a to Room B with function b could be different from Room C with function c to Room D with function d.

The discussions of variables of effort, flow, momentum and power of ABGs are as follows:

- Effort, e, is unit energy, that is, the average of the amount of energy consumed by one person moving within a building. It is equal to 'the sum of total energy consumed by the total number of people moving within the building' over 'the number of total people'.
- Flow, f, is the change that occurred in a unit of time. It is the total number of people change in a unit of time. That is people flow.
- Momentum, p, equals the effort times time, and is the average amount of energy consumed by one person moving within a building during a period of time.
- Power, P, equals the effort times flow, and is the total amount of energy consumed by all people moving within a building in a unit of time.

Then, I, C, R elements of ABGs: I-element, equals momentum over flow, and is 'the amount of average energy consumed by one person during a period of time' over 'people flow'. In the I-element, the value of people flow is 'the average energy consumed by one person during a period of time'.

C-element, equals displacement over effort, and is 'the total number of people change' over 'unit energy'. In the C-element, the average energy consumed by one person is the total number of people change. Within buildings, C-elements can represent spaces. The more the amount of average energy consumed by one person the more number of people change will be.

R-element, is equal to effort over flow, and is ‘unit energy’ over ‘people flow’. In the R-element, the total number of people change over a period of time affects the amount of average energy consumed by one person. That is, the more the people flow is the more the amount of average energy consumed by one person will be and this energy will affect people moving within buildings.

Table 6 shows variables and I, C and R elements of ABGs.

TABLE 6. Variables and I, C, R-element of ABGs.

Effort, ***e***	$\frac{energy_{total}}{people_{total}}$
Flow, ***f***	$\frac{people_{total}}{time}$
Momentum, ***p***	$\frac{energy_{total}}{people_{total}} \cdot time$
Displacement, ***q***	$people_{total}$
Power, ***P***	$e \cdot f = \frac{energy_{total}}{people_{total}} \cdot \frac{people_{total}}{time} = \frac{energy_{total}}{time}$
Energy, ***E***	$energy_{total}$
I-element	$I = \frac{p}{f} = \frac{energy_{total} \cdot time^2}{people_{total}^{\;2}}$
C-element	$C = \frac{q}{e} = \frac{people_{total}^{\;2}}{energy_{total}}$
R-element	$R = \frac{e}{f} = \frac{energy_{total} \cdot time}{people_{total}^{\;2}}$

6. Conclusion and Further Research

ABGs are both qualitative and quantitative models. As a qualitative model, it represents structure information that refers to which elements are used, how they are connected, what functions they play in a system and what are the relations among them and others. It can be used to focus on the important parts that designers would like to discuss without bringing in irrelevant information in. At the same time, it is a quantitative model that enables prediction of the desired system according to the numerical parameters inputs.

With its flexible and extendible characteristics, it is potentially suitable for use in the conceptual stage of design. It could be used for estimating people and goods flows and the energy caused and dissipated by them to evaluate different alternative options and control the efficiencies of space arrangement.

It is expected that ABGs will manifest the strength of bond graphs to integrate knowledge across multiple disciplines. They should have the capacity to represent both the amount of energy consumed by people and goods flow within buildings and the relations between them. ABGs connected with spatial topologies will be further developed and they will have the capacity to integrate a variety of disparate aspects of building and architectural representations. As a consequence, they will form the basis of a unified representation of building as a collection of objects, building as a container of people and their goods and building as a container and transformer of processes.

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