Modeling and Simulation of Dynamic Systems using Bond Graphs

Article · January 2008

CITATIONS
23

READS
3,394

2 authors, including:

Peter C. Breedveld
University of Twente
98 PUBLICATIONS **1,768** CITATIONS

SEE PROFILE

To cite this publication:
Peter C. Breedveld, MODELING AND SIMULATION OF DYNAMIC SYSTEMS USING BOND GRAPHS, in Control Systems, Robotics and Automation, from Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford ,UK, [http://www.eolss.net]

MODELING AND SIMULATION OF DYNAMIC SYSTEMS USING BOND GRAPHS

Peter C. Breedveld, *University of Twente, EWI/CE, P.O. Box 217, 7500 AE Enschede, NL, p.c.breedveld@utwente.nl*

Keywords: modeling, port, bond, bond graph, conceptual element, physical system, engineering system, dynamic behaviour, effort, flow, power, energy, power continuity, entropy, positive entropy production, junction, structure, constraints, iconic diagram, causality, conservation, state, change of state, storage, dissipation, transformation, supply and demand, boundary, environment, boundary condition, constraint, topological constraint, simulation, (generalized) network, topology, constitutive equation

Contents:

Summary

The bond graph notation is defined and its underlying port-concept is explained. Some manipulation techniques are demonstrated and its place in the process of modeling of dynamic system behavior is discussed.

1 Introduction

The topic area that has become commonly known as ‘bond graph modeling and simulation’ should be separated into the *port-based approach to modeling and simulation* at the one hand and at the other hand the *bond graph notation* that is well suited to represent the port-concept. For this reason both the notation and the concepts directly related to the notation will be separated as much as possible from a short introduction into the port-based approach to

modeling, design and simulation. In order to understand the importance of the port-based approach it is also necessary to briefly introduce some generic aspects of modeling and simulation of dynamic behavior of *physical systems*. However, the main emphasis of this contribution lies on the bond graph *notation* and related operations. This explains the four main parts of this contribution after this introduction and some early history (Section 2):

Section 3: Modeling and simulation of dynamic behavior of physical systems
Section 4: Key aspects of the port-based approach
Section 5: Bond graph notation (the main part of this contribution)
Section 6: Introduction to port-based modeling and simulation of dynamic behavior of physical systems in terms of bond graphs

In conclusion some future trends are distinguished in section 7 and section 8 lists the literature.

2 Early history

Bond graphs were introduced by the late Henry M. Paynter (1923-2002), professor at MIT & UT Austin, who, with the introduction of the junctions in April 1959, concluded a period of about a decade in which most of the underlying concepts were formed and put together into a conceptual framework and corresponding notation. In the sixties the notation, e.g. the half arrow to represent positive orientation and insightful node labeling, was further elaborated by his students, in particular Dean C. Karnopp, later professor at UC Davis (Ca.), and Ronald C. Rosenberg, later professor at Michigan State University (Mich.) who also designed the first computer tool (ENPORT) that supported *simulation* of bond graph models. In the early seventies Jan J. van Dixhoorn, professor at the University of Twente, NL and Jean U. Thoma professor at the University of Waterloo, Ont. were the first to introduce bond graphs in Europe.
These pioneers in the field and their students have been spreading these ideas worldwide. Jan van Dixhoorn realized that an early prototype of the block-diagram-based software TUTSIM could be used to input simple causal bond graphs, which, about a decade later, resulted in a PC-based tool. This work laid the basis for the development of a port-based computer tool at the University of Twente ('20-sim' or 'Twente-sim'). He also initiated research in modeling more complex physical systems, in particular thermofluid systems.
In the last two decades bond graphs either have been a topic of research or are being used in research at many universities worldwide and are part of (engineering) curricula at a steadily growing number of universities. In the last decade industrial use has become more and more important. (see Mathematical Models, Physical Laws, Electrical Networks, Graph Theory, Variational methods, Elements of Control Systems)

3 Modeling and simulation of dynamic behavior of physical systems

Behavior of *macrophysical systems* is commonly constrained, either implicitly or explicitly, to the behaviors that satisfy the basic principles of physics, viz. *energy conservation*, *positive entropy production* and *power continuity* (see *General Models of Dynamic Systems*). Furthermore, various physical *domains* are distinguished that are each characterized by a particular *conserved quantity* (Table 1). Note that each of these domains has analogous basic behaviors or *ideal behaviors* with respect to energy, viz. *storage*, *irreversible transformation*,

reversible transformation, *distribution*, *supply & demand*. Although *transport* at a finite speed is often considered a basic behavior, it is not listed as it can be considered to consist of a combination of storage and transformation.

Computer simulation requires that these behaviors are finally described by computer code that represents a numerically solvable mathematical model of which the solution in the form of a time trajectory of the *states* and consequently of all variables that depend on these states, can be numerically approximated (*digital simulation*). In case of *analog* (as opposed to digital) *simulation* electric circuits based on operational amplifiers mimic the mathematical operations of the model in terms of equations. By contrast, electric circuits that are analogues of the original system can also be used to mimic behavior, but this form of simulation has become almost extinct due to the increase of power of digital computing.

Mixed analog and digital simulation is called *hybrid simulation*.

The final aim of modeling for digital simulation is a set of *state equations* and algebraic relations, to be generated either by hand or automatically on the basis of a description in terms of other concepts. (see Modeling and Simulation, Computational Methods)

The crucial issues in the process of modeling of dynamic behavior are:

- Determination of the purpose of the model in a specific *problem context* in order to be able to judge whether a model is *competent* for a particular problem context. In other words: no generic, 'true' (sub)model exists by definition in the sense that (sub)models are not exact copies of the (sub)systems to be modeled, but they may be competent to support the solution of a *particular problem* related to the actual system. Note that this problem may be related to the past (trouble shooting), to the future (conceptual design) and to the present (model-based, real-time control, including the control of user interfaces in simulators).
- Identification of *dominant* and relevant *behaviors* and decomposition into *elementary behaviors*.
- Generation of a *conceptual structure* that combines these elementary behaviors into a computable dynamic model of the relevant system behavior(s).

	f *flow*	e *effort*	$q = \int f\mathrm{d}t$ *generalized displacement*	$p = \int e\,\mathrm{d}t$ *generalized momentum*
electromagnetic	i current	u voltage	$q = \int i\mathrm{d}t$ charge	$\lambda = \int u\mathrm{d}t$ magnetic flux linkage
mechanical translation	v velocity	F force	$x = \int v\,\mathrm{d}t$ displacement	$p = \int F\mathrm{d}t$ momentum
mechanical rotation	ω angular velocity	T torque	$\theta = \int \omega\mathrm{d}t$ angular displacement	$b = \int T\mathrm{d}t$ angular momentum
hydraulic / pneumatic	φ volume flow	p pressure	$V = \int \varphi\mathrm{d}t$ volume	$\Gamma = \int p\mathrm{d}t$ momentum of a flow tube
thermal	T temperature	f_S entropy flow	$S = \int f_S\mathrm{d}t$ entropy	
chemical	μ chemical potential	f_N molar flow	$N = \int f_N\mathrm{d}t$ number of moles	

Table 1: Domains with corresponding flow, effort, generalized displacement and generalized momentum

4 Key aspects of the port-based approach

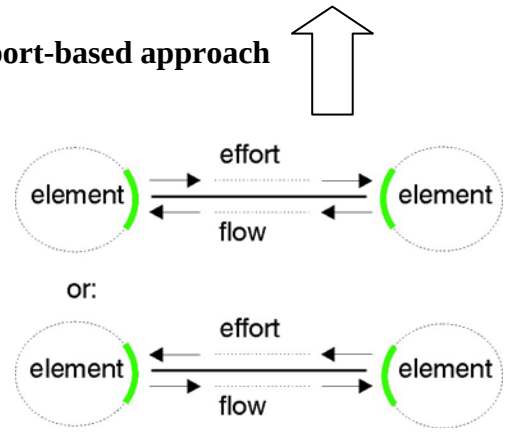


Figure 1: Bilateral signal flows between ports

The concept of a power *port* was introduced by Harold A. Wheeler in 1949 for electric circuits and extended by Henry M. Paynter to other physical domains (hydraulic, mechanic, etc.) in the early fifties. The paradigm shift that is required to make the transition from a signal-based modeling approach in which inputs of (sub)systems are related to outputs of (sub)systems by some functional relationship, consists of the acceptance not only that the basic form of interaction between (conceptual) parts of a physical system always contains an input signal as well as an output signal ('back effect') that is called *conjugate* to the input signal and related to the power of the interaction, but also, and more importantly, that nothing more about the computational direction of these signals is a priori known than that they are opposite, thus resulting in a *bilateral signal flow* that is intrinsic to the generic concept of a '*relation*' (figure 1).

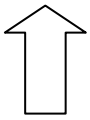
Although this seems rather trivial or even self-evident, the signal-based point of view appears so deeply settled in our conceptual world that it not only leads to all sorts of complex formulations in order to express the port-based ideas in classical mathematical terms, but it also results in the common opinion that a port-based representation is more abstract than a representation in terms of mathematical operations on signals. This is not only due to a historic preoccupation with a signal-based view, but also to the human inclination to approach the world around us from an anthropocentric point of view: a human being provides an input to an object of interest and observes its output. Although quantum mechanics has drawn more attention to the role of the observer in measurement processes, it appears still hard to accept that the human being generally does not just provide an input to a system, but that it truly interacts with it, in the sense that in a generic sense the system 'pushes back' during interaction.

Sequential representations like the lines of a text in natural language or a sequence of mathematical relations are not optimally suited to represent interactions between conceptual parts of a model, as all relations are simultaneously present in a port-based model and do not necessarily have a chain-like structure.

Insight in simultaneously present relations thus requires a graphical representation. *Iconic diagrams* like electric circuit diagrams and simple mechanical schematics represent relations simultaneously, but have the disadvantage of being linked to a specific domain and have less room for direct connection with analytical tools. By contrast, the bond graph notation achieves both domain independence and the option to extend the notation as to easily connect with analytical tools. The bilateral signal flow in a bond graph consists of the power conjugate variables, viz. the equilibrium-establishing *flow* and the equilibrium-determining *effort*. The terminology *equilibrium-determining* variable refers to the fact that equilibrium is determined by differences in effort being zero. The terminology *equilibrium-establishing* variable refers

to the fact that equilibrium is established by an exchange of the conjugate stored quantity, i.e. a rate of change or flow of that quantity.

5 Bond Graph Notation



5.1 Introduction

Bond graphs are *labeled di-graphs*: the *edges* are called *bonds* and represent the *bilateral signal flow* of the power-conjugate variables effort and flow. The common convention for the position of the symbols for the effort and flow variables in a bond graph with respect to their bond is that efforts are written above or to the left of a bond and flows below or to the right. As this is ambiguous when the bond has a 'north-west inclination' (considering the top of the paper to be 'north') the symbol for the bond orientation is also used to indicate the position of the flow and is supposed to be in line with the common convention. This edge orientation of the di-graph is represented by a little stroke that forms a *half-arrow* with the line representing the edge. This is the typical appearance of a bond (cf. the bond graph fragments in Table 2).

5.2 Node types

A labeled *node* represents a basic behavior. There are *nine* basic behaviors that can be categorized in *five* groups of basic physical behaviors:

1) Storage ('first law', *energy conservation*)
2) Supply and demand (*boundary conditions*)
3) Reversible transformation (configuration constraints, *interdomain* connections)
4) Distribution (topological constraints, *intradomain* connections)
5) Irreversible transformation ('second law', *positive entropy production*)

Ad 1) The most common approach to port-based modeling distinguishes, similar to modeling electrical networks and simple mechanical systems, two *dual* types of storage: capacitive or *C-type* storage and inertial or *I-type* storage. Examples of C's: electrical capacitor, spring, etc. Examples of I's: coil, mass, etc.

> Note that this approach symmetrizes the role of efforts and flows in the models, such that the distinction between equilibrium-establishing variable and equilibrium-determining variable cannot be used for variable identification during modeling. The Generalized Bond Graph approach introduced by the current author in 1979 and further developed between 1979 and 1984 circumvents this problem by using one type of storage and splitting domains that are explicitly connected by a so-called *symplectic gyrator*. Although this approach provides more insight during modeling and provides a better link to mathematical analysis in the form of port-Hamiltonian systems, it is not discussed herein to prevent confusion at this introductory stage.

Ad 2) Furthermore, there are two, dual types of *boundary conditions* (called Dirichlet and Neumann conditions in the context of partial differential equations): *sources* of effort (*Se-type*) and sources of flow (*Sf-type*). Examples of Se's: voltage source, pressure source, etc. Examples of Sf's: current source, fluid-flow source, etc.

Ad 3) The *reversible transformations* appear in dual form too: the *non-mixing*, *reciprocal* transformer or

TF-type transducer and the *mixing*, *antireciprocal* gyrator or *GY-type* transducer. Examples of TF's: gearbox, positive displacement pump, etc. Examples of GY's: centrifugal pump, turbine, etc.

Ad 4) The *topological constraints* also appear in dual form: the so-called *0-junction* and *1-junction*.
The fact that these topological constraints are represented by *nodes* of the graph are the most powerful feature of the bond graph representation, but at the same time the most uncommon and potentially confusing aspect. The 0-junction not only represents a generalized, i.e. domain independent, Kirchhoff Current Law (KCL), but also the identity of the conjugate efforts, such that it can be considered to represent a common effort. Being the dual node of a 0-junction, a 1-junction not only represents a generalized, i.e. domain independent, Kirchhoff Voltage Law (KVL), but also the identity of the conjugate flows, such that it can be considered to represent a common flow.
The common approach to model mechanical constraints at the *position* level is related to the dual nature of the *position* variable, both *energy state* and *configuration state*. Merely from an energy point of view the mechanical constraints lie at the velocity level and should be treated as such. However, the description of the variable configuration requires a formulation at the *position* level, commonly resulting in *position modulation* of the mechanical junction structure.

Note that an arbitrary multiport with two constraints, viz. *power continuity* and *port symmetry* can be proven to be either a 0- or a 1-junction, i.e. a linear, non-parameterized multiport. No assumption about domain or form of the constitutive relations is required.
However, the (topological) structure may not be constant. In that case the junction may depend on a *logical state* that, if it were, switches it 'on' and 'off'. This 'switched junction' is represented by adding the letter X to the junction symbol, i.e. X0 and X1, and is modulated by a Boolean signal. In the 'off'-state all connected ports have zero power.

The storage elements store energy reversibly and are consequently not power-continuous. The *sources* supply power to the system (from the environment) or drain power from the system (to the environment) and are also not power continuous with respect to the system accordingly. In fact, *sources* can be considered storage elements that are infinitely large with respect to the storage processes of interest. Other forms of power discontinuity cannot exist due to the energy conservation principle, i.e. all other elements should be power continuous in principle. The transducers are power continuous two-ports, while the junctions are power continuous multiports, i.e. with two or more ports. Note that the junctions are not parameterized.

Ad 5) The *irreversible transducer* does not change type when dualized. In principle, it is also a power-continuous two-port, which will appear an uncommon conclusion at first sight. It is a domain-independent representation of all entropy producing processes, like electrical & fluid resistance, friction and other so-called 'losses', including thermal resistance, of which the second port is always thermal with a constitutive relation that is nonlinear by definition (linear two-ports can be proven to be reversible). However, as the temperature variations of the environment are often assumed to be sufficiently slow with respect to the dynamics of interest in the system as to be able to consider the environmental temperature constant, the energy of the system can be replaced by its *Legendre transform* with respect to the entropy, i.e. the so-called *free energy*, while omitting the thermal port that produces the thermal power related to the entropy production of an irreversible process. This reduces the irreversible, power continuous two-port transducer into a virtually *power discontinuous*, i.e. '*free energy dissipating*' *one*-port that is commonly called *dissipator*, *resistor* or *damper*. Note that the assumption that the temperature variations of the environment are often sufficiently slow with

respect to the dynamics of interest in the system does often not hold in the latter case, viz. the resistor of the mechanical domain, but may also be violated by the continuously increasing miniaturization that reduces the thermal time constants: less material and shorter distances mean less thermal storage and less thermal resistance, resulting in smaller time constants (RC-times).

Summarizing, the following *nine basic node-types* are distinguished:

- 4 one-ports: C, I, (M)Se, (M)Sf;
- 2 two-ports: (M)TF, (M)GY;
- 2 *n*-ports with *n*>1: 0, 1;
- 1 one- or two-port: (M)R(S).

The one-ports are *power discontinuous*, the two-ports and multiports are *power continuous*.

The letter M in the node symbol of some of the parameterized nodes stands for '*modulated'*, expressing that the constitutive equation can depend on an external signal (*modulation*) without changing the nature of the node or affecting the power balance. Storage elements are parameterized, but not modulated in principle, as this would violate the basic concept of storage. However, when it is obvious that either the power or the dynamic interaction related to one of the ports of a multiport version of the storage element can be neglected at all times with respect to the other port(s), *modulation* can be used (e.g. a variable capacitor in a receiver circuit).
Modulation usually requires '*bond activation*', i.e. the bond, a bi-lateral relation, reduces to a uni-lateral relation, the signal, due to the fact that the other conjugate variable can be neglected in the particular context. The terminology refers to the fact that an *active* element, e.g. an operational amplifier, is required to obtain this situation. However, decomposition of nonlinear elements can also lead to junction structures containing internally modulated elements that are modulated by 'true signals' in the sense there is no conjugate variable by definition. This means that *internal modulation* that is related to decomposition cannot be considered bond activation.
Internal modulation can be useful in principle, but should be used as a modeling instrument with great care as it can be used, in particular in case of internal modulation by one of the port variables of the modulated node, to construct one 'elementary' behavior out of another one. For example, a voltage source directly or indirectly modulated by its own conjugate flow behaves like a resistor, etc. In other words: *internally modulated* sources not only violate the basic definition of a source, they can also be used to construct virtually 'anything'. Nevertheless, if used with sufficient care, they can enhance insight in specific cases, such that a 'veto' on their use would be inappropriate.

5.3 Constitutive relations

One *constitutive relation* should characterize each port. The node type constrains the possible forms of these constitutive relations. Often, relatively small variations around the origin can be linearly approximated, resulting in just one parameter per port, e.g. capacitance, resistance, etc. These constitutive parameters always consist of a combination of geometric parameters and material parameters. Note that if a configuration is made time-variant, a consequence can be that a geometric parameter becomes an *energy state* and requires an additional power port of a storage element (e.g. condenser microphone, coil with moving core, etc.) or a signal port of the other elements resulting in *state-modulation*.

However, as most physical variables have some upper limit, *saturation*, and thus nonlinearity, will occur in all constitutive relations of parameterized ports. Examples are: the speed of light that shows that the parameter 'mass' cannot remain constant at all times, breakdown voltage of a capacitor, force at which a spring breaks, magnetic saturation, etc. It depends on the context whether or not such a nonlinear range should be included in the model.

The storage ports are somewhat exceptional as the relation between the conjugate variables effort and flow contains two stages: the first stage is always *integration with respect to time* into an *energy state*. This operation can, if necessary, be inverted into a differentiation with respect to time although this means that physically relevant information about the *initial condition*, i.e. the initial content of the storage element, cannot be given a place in the model (cf. the later discussion of causal port properties in section 5.6.2). The second part is an unambiguous functional relation between the (extensive) *energy state* (*q*- or *p*-type) and the conjugate power variable (intensive state). The latter relation is not a priori constrained, except for the constraint that if a node contains more than one storage port, it should satisfy the *Maxwell reciprocity conditions* in order to satisfy the energy conservation principle. However, qualitative properties of a storage (multi)port, like *intrinsic stability*, may lead to additional constraints like positive-definiteness and positive diagonal elements of the Jacobian.
The storage ports can be classified as '*history ports*', while all other ports belong to the class of '*non-history ports*'. Note that at the signal level other forms of history operations can exist, like flip-flops, sample and hold, pure integration, etc. This distinction is helpful when preparing a numerical simulation. The presence of history ports is required to obtain dynamic behavior.
If measurement of the relation between intensive and extensive states results in a loop in the port characteristic (hysteresis), the port that is observed cannot be simply represented by one storage port, but contains at least one other storage port through which power is exchanged. If this port is connected to a dissipative port, the cycle will have to be clockwise due to the positive entropy production principle (cf. section 5.7.3 on multiports at page 24).

Relations between efforts and flows of all other elementary ports are algebraic, although it can still be the case that states modulate these elements. This state modulation particularly occurs in mechanism models in which the geometric constraints can be represented by position-modulated transformers and their multiport generalizations. The importance of choosing variables that lead to insightful representations of complex mechanisms that can be easily manipulated should not be underestimated but goes beyond the scope of this contribution.
The constraint on an R-port is that the functional relation should satisfy the positive entropy production principle. For the common orientation definitions (i.e. one-ports *except sources* positive *towards* the port; two-ports one inward, other port outward) this means that this function cannot be in the second or fourth quadrant and thus has to intersect with the origin. Note that there is no demand of linearity such that a *diode* belongs to the class of electrical R-ports, even though it does not have an ohmic (i.e. linear) resistance. Similarly, a check valve belongs to the class of hydraulic R-ports. Friction in a mechanical contact with Coulomb and static friction and the Stribeck effect can still be described by a nonlinear R-port, although its implementation requires special attention from port-based perspective.
A source is degenerate in the sense that its constitutive 'relation' merely states that there should be *no relation* between its conjugate variables: the only constraint is that the imposed variable is independent of the conjugate variable. Note that so-called 'non-ideal sources' violate this constraint, but can always be considered a combination of an ideal source with

one of the other node types (usually a resistor that represents the so-called internal resistance). However, non-ideal *sources* influence the dynamic characteristics of a system model while an ideal source does not.

The constitutive relations of two-ports are all *multiplicative* in form: the multiplication factor (transformation or gyration ratio) can depend on time or system state, and, in some cases, on the port variables, in which case modulation changes into nonlinearity. An example of the latter situation is a centrifugal pump or turbine: a nonlinear GY (often incorrectly written as a 'port-modulated' MGY) with a hydraulic port (p, φ) and a rotation port (T,ω) with ratio ($a\omega$+$b\varphi$), i.e. $p=(a\omega+b\varphi)\omega=a\omega^2+b\varphi\omega$ and $T=(a\omega+b\varphi)\varphi=a\omega\varphi+b\varphi^2$, where a and b depend on the geometry and the fluid properties.

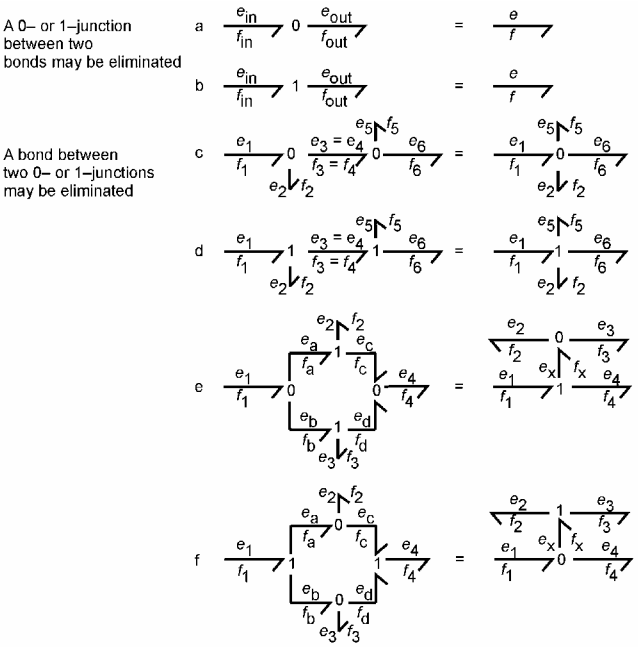


Table 2: Equivalence rules for simple junction structures

5.4 Relation to other representations

Given the unambiguous definitions of the basic modeling concepts any alternative representation of these concepts, like an electric circuit diagram or a simple iconic representation of a mechanical system, often collectively called 'ideal physical model' or IPM, can be 'translated' into a bond graph. Note that only the bond graph is domain-independent. A translation from a bond graph into a domain-dependent notation of one or more given domains is also possible, although the following procedure allows that its inverse has multiple solutions.

A *standard procedure* for the *translation of an IPM into a bond graph* contains the following steps (specifics between brackets apply to the mechanical domain that is treated in a dual way due to the common choice of variables, i.e. the force-voltage analogy):

1. Identify the domains that are present.
2. Choose a *reference* effort (velocity *reference* and direction) for each of the domains (degrees of freedom).
3. Identify and label the other points with common effort (velocity) in the model.

4. Identify, classify and accordingly label the ports of the basic one- and two-port elements: C, I, GY, etc. in the model. A label consists of a node type and a unique identifier, e.g. in the linear case the constitutive parameter connected by a colon.
5. Identify the efforts (velocities) and effort differences (relative velocities) of all ports identified in the previous step.
6. Represent each effort by a 0-junction, (each velocity by a 1-junction). Use a 1-junction (0-junction) and bonds to construct a relation between each effort difference (relative velocity) and the composing efforts (velocities) as follows, taking care that each effort difference (relative velocity) is explicitly represented by a 0-junction (1-junction):

7. Connect all ports identified in steps 4 and 5 to the corresponding junctions. Note that after this step all of the ports identified in step 4 are directly connected to a 0-junction (1-junction) only.
8. (optional) Simplify the bond graph where necessary according to the equivalence rules in Table 2.

These steps not only support this translation process, but also give a better insight when dynamic models are directly written in terms of a bond graph as well. In that case steps 1, 3, 4 and 5 should be changed from a translation of already made modeling choices into the modeling choices themselves.
Note that this process is merely intended to establish a link between familiar representations and a bond graph representation. It does not suggest that the use of bond graphs to support modeling always takes place on the basis of an existing IPM. On the contrary, the process of making modeling choices is supported best by direct application of the bond graph representation, especially when it is causally augmented as will be shown in section 6, where the advantage of a bond graph as an alternative model 'view' will be illustrated.

5.5 Systematic conversion of a simple electromechanical system model into a bond graph representation

In order to demonstrate the relationship between the domain-independent bond graph representation of a model and a domain dependent representation, e.g. the *iconic diagram* of the model of the elevator system in figure 2a, a systematic conversion is demonstrated in figure 2c through 2j following the eight steps described in the previous section. Note that this conversion ignores the automatic feedback on modeling decisions from a bond graph, as the modeling decisions have already been made. The latter process is demonstrated in section 6.

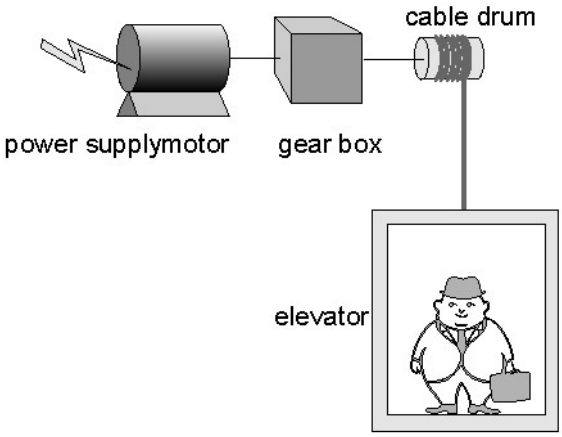


Figure 2a: Sketch of an elevator system

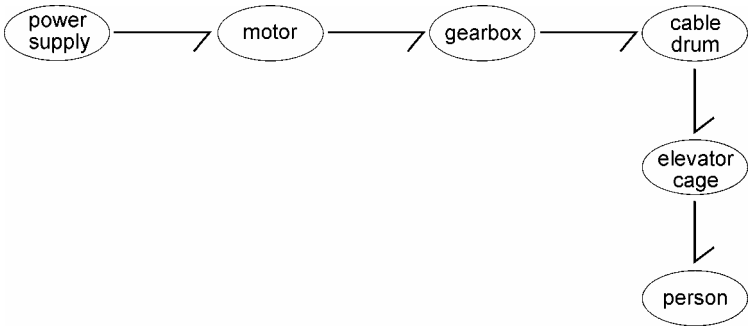


Figure 2b: Word bond graph

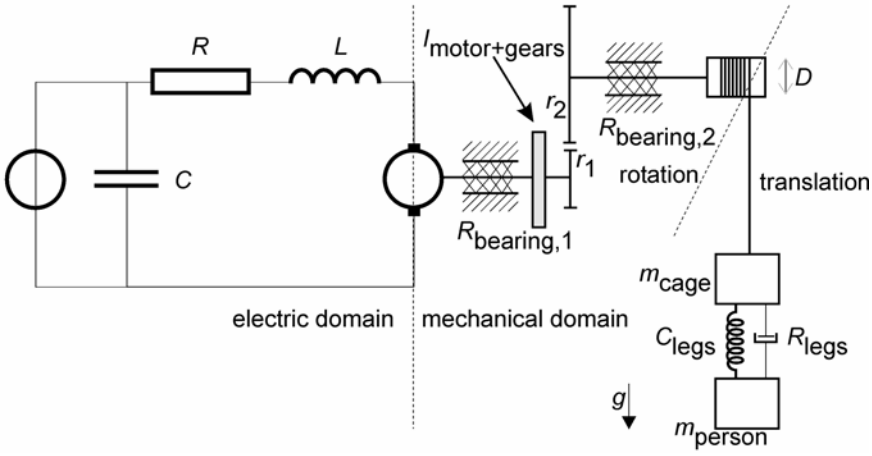


Figure 2c: Iconic diagram of the IPM of the elevator system (step 1)

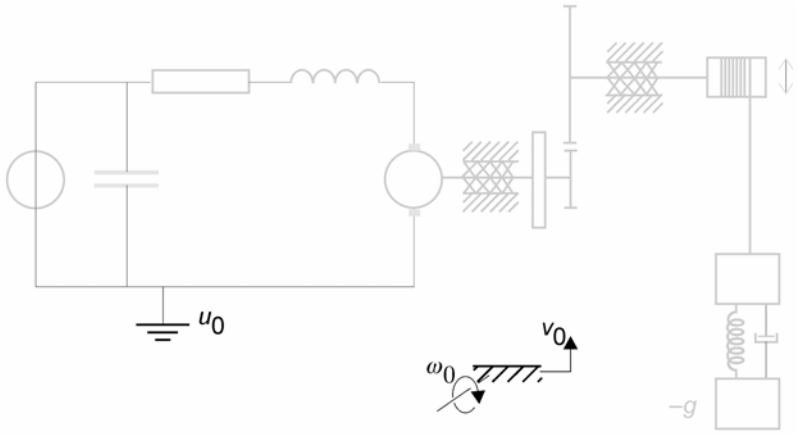


Figure 2d: The IPM with references (step 2)

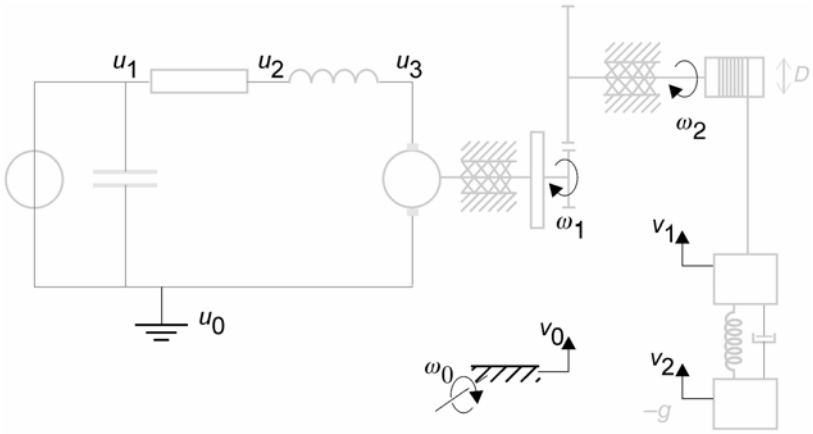


Figure 2e: The IPM with relevant voltages and (angular) velocities indicated (step 3)

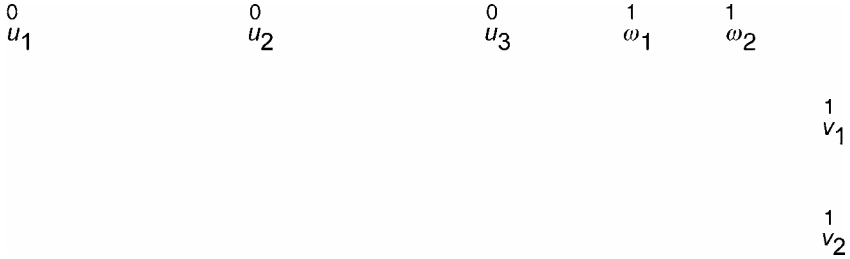


Figure 2f: Representation of voltages by 0–junctions and of velocities by 1–junctions (step 4)

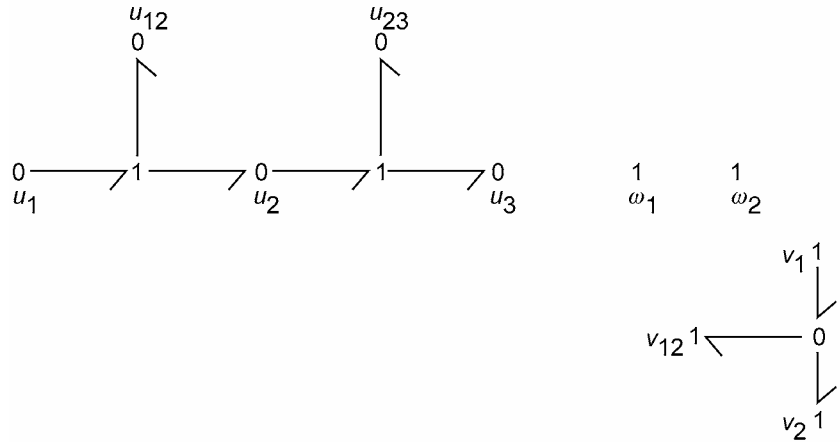


Figure 2g: Construction of the difference variables (step 5&6)

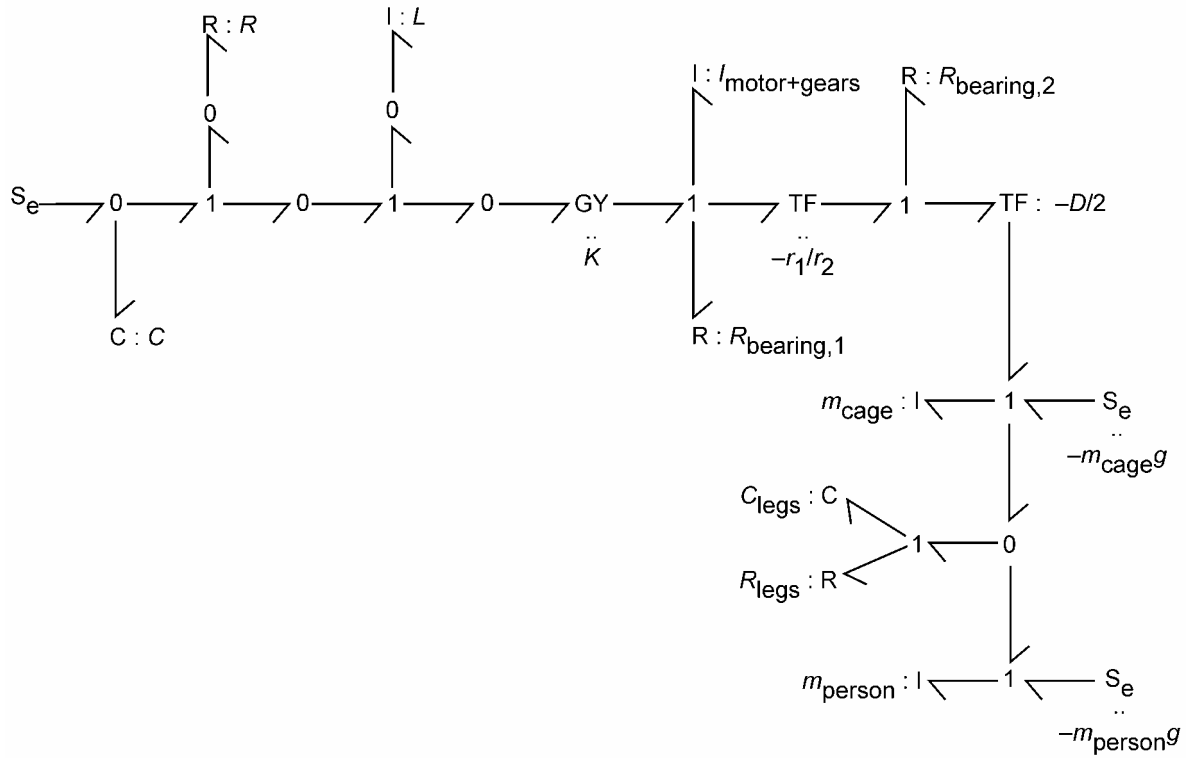


Figure 2h: Complete bond graph (step 7)

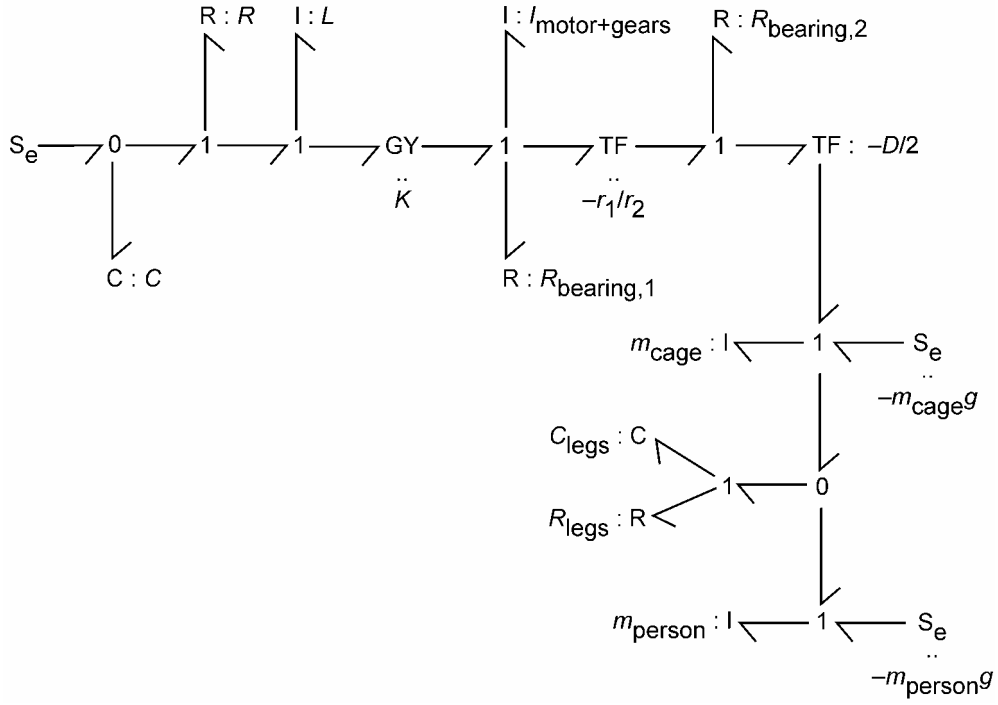


Figure 2i: Simplification of the bond graph (step 8a)

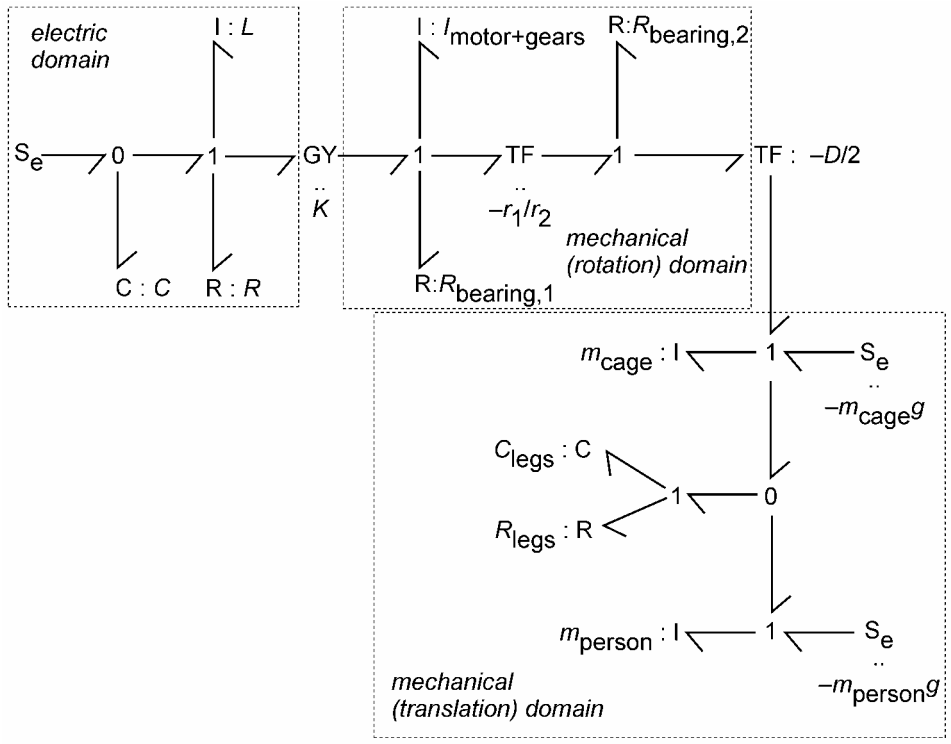


Figure 2j: Simplification of the bond graph (step 8b)

5.6 Causality

5.6.1 Notation

A bond graph uses the same notation for all domains. The advantage of this feature will become clear after the introduction of some of the available analysis options like finding *causal paths* and their loop gains using impedances (cf. 5.6.7).

However, there is much more to be gained when the final directions of the signals present in a bond graph as bilateral signal flows are explicitly shown in the bond graph itself, in particular to compare the different options. As there are only two possibilities per bond, a choice has to be made based on the properties of each of the ports that is attached to it. Before demonstrating how this is done, a notation is defined for the representation of this so-called (computational) *causality* (to be distinguished from the concept of 'causality' in systems theory that refers to the 'arrow of time'). A short stroke, called '*causal stroke*', perpendicular to the bond at one of its ends, indicates the (computational) direction of the effort variable. Accordingly, the other, so-called 'open end' of the bond represents the computational direction of the conjugate flow variable (Figure 3). Note that the position of the causal stroke is completely independent of the position of the half arrow that indicates the positive orientation, which is therefore omitted in figure 3.

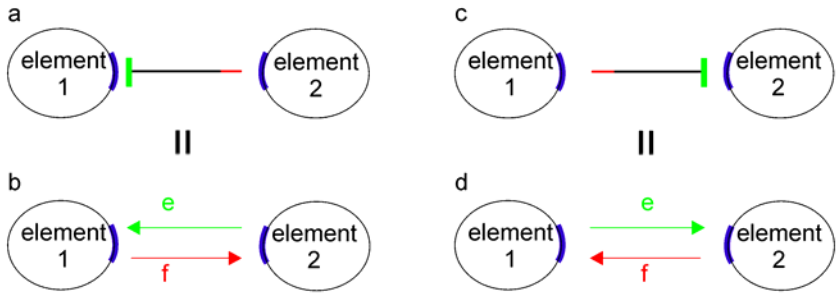


Figure 3: Definition of the causal stroke

5.6.2 Causal port properties

Each type of port has a specific causal property. The following main classes of causal port properties can be distinguished:

- Ports with *fixed causality*:
  There is only one option for the causality by definition. Examples are the Se (fixed effort-out causality) and the Sf (fixed flow-out causality). However, fixed causalities may also result from the non-invertibility of a constitutive relation that characterizes a port. This type of fixed causal port should be treated differently from the source-type of port.
- Ports with *preferred causality*:
  For some reason, depending on the type of model manipulation, a causal form can have preference. The most common example is the preferred integral causality of storage ports, as *numerical integration* is preferred over numerical differentiation during simulation, apart from the physical argument that a physically meaningful initial condition can only be given a place in the integral form. However, for analysis purposes, for instance direct application of Mason's loop rule (see Elements of Control Systems) or finding the order of the system, differential causality may be preferred during causality assignment as well.
- Ports with *arbitrary causality* or *free causality*:
  In some cases the causality can be chosen at will. An example is an ohmic resistor: the voltage can be computed from the current or vice versa.
- Ports with *causal constraints*:
  Multiports can have causal constraints between their ports. Examples are the junctions (only one flow-out causality at a 0-junction and only one effort-out causality at a 1-junction), TF (only one effort-out and one flow-out causality) and a GY (either two effort-out causalities or two flow-out causalities).

5.6.3 Causality assignment

Based on these causal port properties all sorts of causality assignment algorithms can be applied for different purposes. The common purpose is to write the model equations in a form suitable for simulation, i.e. maximizing the number of storage ports with integral causality. The most common algorithm is the so-called 'sequential causality assignment procedure' (SCAP) that was developed by the bond graph pioneers Dean Karnopp and Ronald Rosenberg in the mid-sixties. It is not perfect in the sense that it fails in some rare cases, but generally it not only generates a set of computable equations, but it also gives feedback on modeling decisions. This is the reason for no discussing a more robust, but also more complex method

that can be used for computer implementation. A short description of the steps of the SCAP is:

1) If present, assign a fixed causal source port and propagate this causality along the nodes with causal constraints until propagation terminates due to multiple possibilities. Repeat this step until all source ports are augmented with a fixed causality. If propagation leads to conflicts with other fixed causalities the model is ill-posed. If propagation leads to conflicts with preferred causalities the model contains differentiations of the inputs (input-dependent 'states'). However, also those storage ports that obtain integral causality as a result of propagation of the fixed causality of one or more source-ports do not result in independent states: only their initial conditions can be freely chosen, the rest of their behavior is fully dictated by the source port(s), such that they do not contribute to the characteristic dynamic behavior of the model. If all bond ports are causal at this point, the model does not have its own dynamics, but is completely determined by its inputs.
2) If present, assign a fixed causal port that is not a source port and propagate this causality along the nodes with causal constraints until propagation terminates due to multiple possibilities. Repeat this step until all ports of this type are augmented with a fixed causality. If propagation leads to conflicts with other fixed causalities or with preferred causalities the *causal path* (signal loop) that causes the conflict should be analyzed symbolically as to obtain a solution. This propagation should not lead to non-preferred causalities as this would lead to misleading conclusions about the order of the model), unless the fixed causal port is a storage port itself. In that case the non-preferred causality is similar to the dependency that can occur during the next step.
3) If present, assign a preferred causal port and propagate this causality along the nodes with causal constraints until propagation terminates due to multiple possibilities. Repeat this step until all ports with preferred causality are assigned. If propagation leads to conflicts with other preferred causalities the model contains dependent states (no initial condition).
4) If not all ports are causal at this point, there are at least two ports with arbitrary causality, resulting in a number of possibilities that all will lead to *causal paths* between ports of elements that are described by algebraic constitutive relations thus causing algebraic signal loops. Choose the causality of these ports not only in such a way that the number of algebraic loops is minimized, but also in such a way that the loop gains of these algebraic loops are smaller than one as much as possible.

A causal bond graph can always be straightforwardly expanded into a *block diagram* or signal flow graph. The experienced user will be able to obtain the same information from a causal bond graph as from a *block diagram*, viz. the computational structure, while the bond graph already represents the physical structure in a domain-independent way. This demonstrates one of the main advantages of the bond graph representation: it can be seen immediately how changes in the physical structure affect the computational structure and thus the dynamic characteristics vice versa. This is particularly helpful during conceptual design, troubleshooting and solving problems related to numerical simulation.
Note that not any *block diagram* or signal flow graph can be converted into a causal bond graph as they generally do not contain conjugate port variables. However, an attempt to convert a *block diagram* that represents the computational structure of a model of a physical system into a bond graph can be a quite insightful experience as it may explicate earlier choices about the nature of the physical ports as well as eliminations of physically relevant variables.

5.6.4 Conversion of a causal bond graph into a block diagram

As a causal bond represents a bi-lateral signal flow with fixed directions, a causal bond graph (e.g. figure 4a) can be expanded into a block diagram in three to four steps:

1) all node symbols are encircled and all bonds are expanded into bilateral signal flows according to the assigned causality (figure 4b).
2) all constitutive relations of each node are written into block diagram form, according to the assigned causality of each port; zero-junctions are represented by a signal-node for the efforts and a summation for the flows, while one-junctions are represented by a signal-node for the flows and a summation for the efforts(figure 4c).
3) all signals entering a summation resulting from a junction are given a sign corresponding to the half-arrow direction: if, while traveling from causal input to causal output, the bond orientation does not change (this does not exclude an orientation opposite to the signal direction!), then a plus sign is added representing a positive contribution to the summation; by contrast if the bond orientation does change, then a minus sign is added representing a negative contribution to the summation (figure 4d). In principle, a complete block diagram is obtained at this point. However, its topology is not common due to the location of the conjugate signals. This may be omitted in the next step.
4) Optional: Redraw the block diagram in such a way that the inputs are at the left-hand side and the outputs (observed variables) are at the right-hand side (figure 4e) with the integrators in the forward path. The block diagram may be manipulated according to the standard rules for block diagrams as to obtain a canonical form.

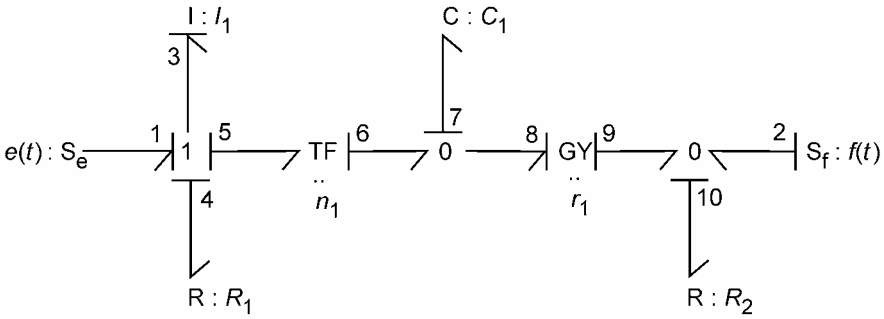


Figure 4a: Causal bond graph

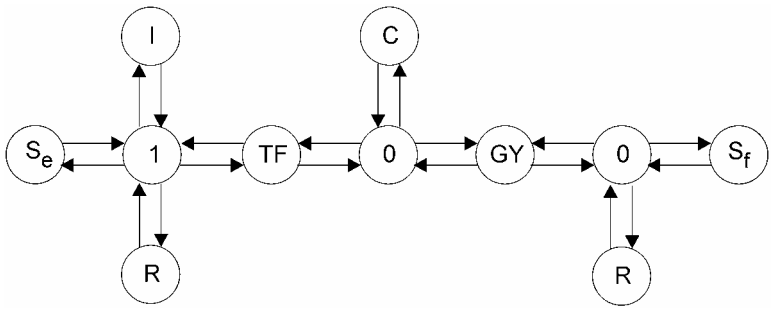


Figure 4b: Expansion of causal bonds into bilateral signals

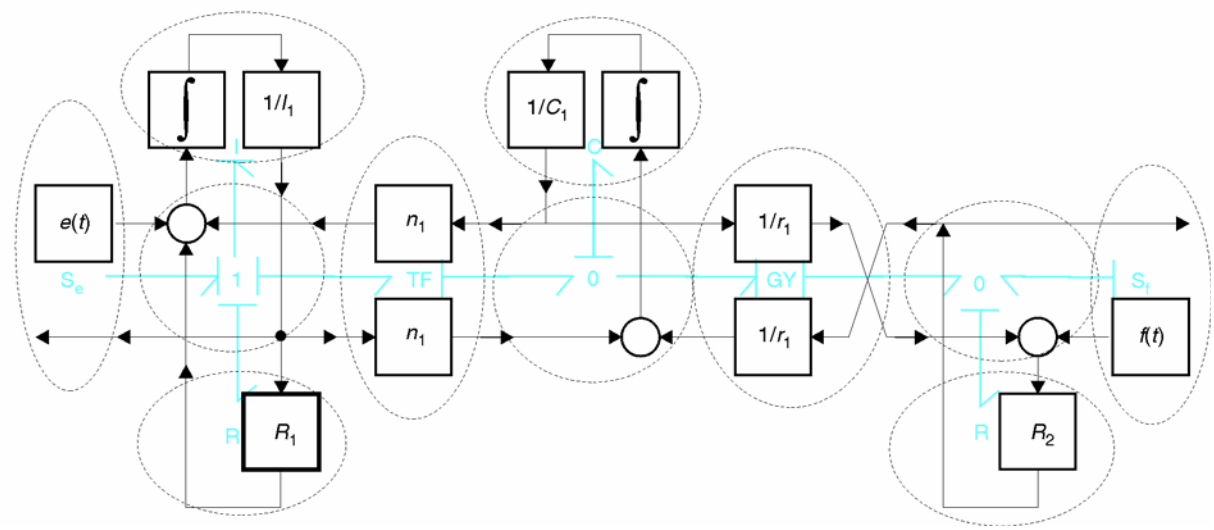


Figure 4c: Expansion of the nodes into operational blocks

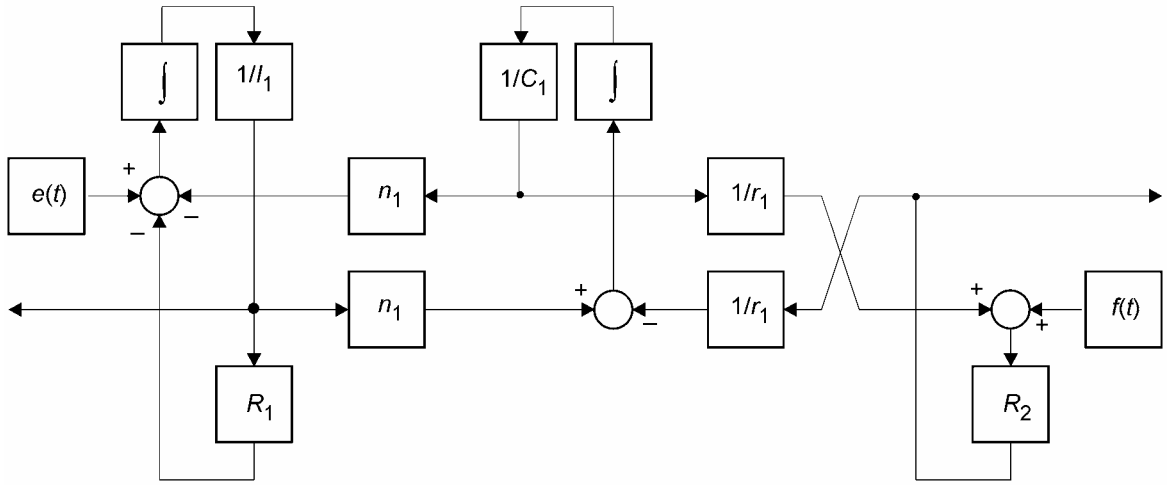


Figure 4d: Addition of signs to the summations

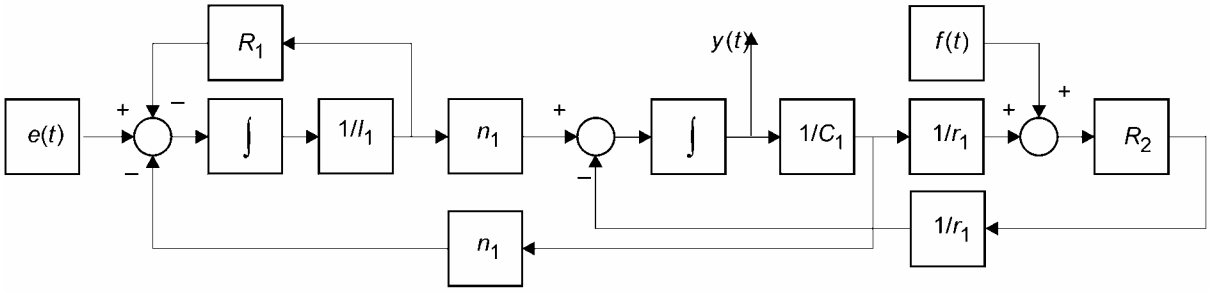


Figure 4e: Conversion into conventional form

The procedure to obtain a signal flow graph is completely analogous to the above procedure as all operations represented by blocks, including the signs of the summations, are combined as much as possible and then written next to an edge, while all summations become nodes, as

signal nodes can be distinguished from signal summation points by observing the signal directions (signal node has only one input, summation has only one output).

5.6.5 Causal paths

A bond path between two ports of the type C, I, R, Se, or Sf via the (G)JS containing 0, 1, TF and GY is called a *causal path* if the sequence of the causal strokes is such that they have one direction with the exception of a path through a GY where this causal stroke direction is always altered. A causal path is equivalent with a signal loop in a block diagram or signal flow graph except for the case that a source port (Se or Sf) is part of the path (cf. figure 5).

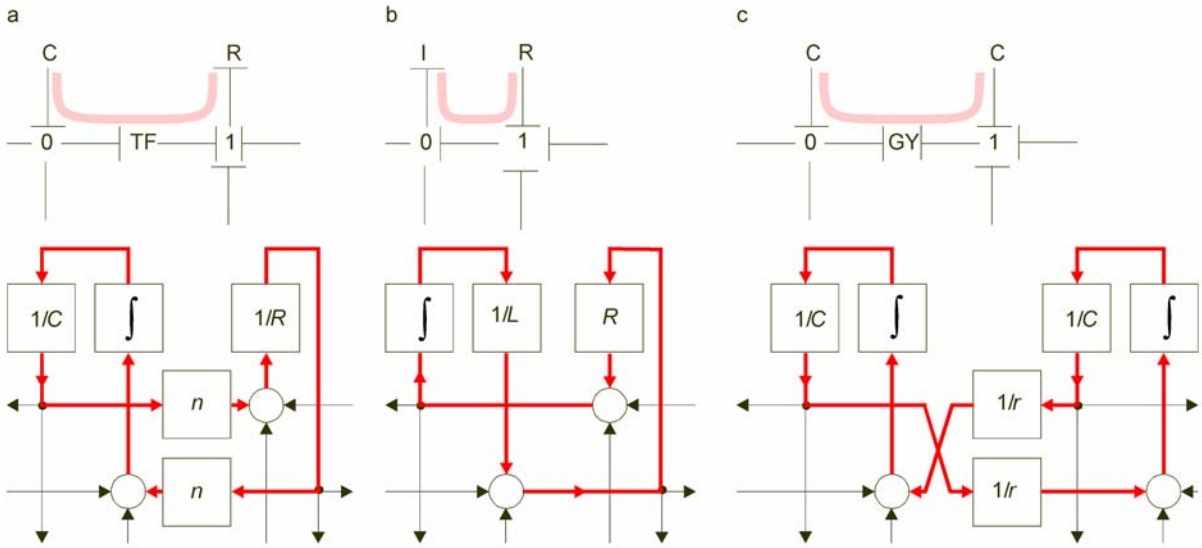


Figure 5: Causal paths and block diagram expansion to signal loops

5.6.6 Generation of a set of mixed algebraic and differential equations

An arbitrary bond graph with n bonds contains $2n$ conjugate power variables, $2n$ ports and $2n$ corresponding port relations (constitutive relations). If a bond graph is made causal, the order in which the causal strokes are assigned to the bonds can uniquely label the bonds and their corresponding efforts and flows by using the sequence numbers of this process as indices. Next the constitutive relation of each port is written in the form that corresponds to the assigned causality. This results in a mixed set of $2n$ algebraic and first-order differential equations in an assignment statement form. Note that the differential equations that belong to storage ports in preferred integral causality have a time derivative at the left-hand side of the assignment statements, indicating a 'postponed' integration, if it were. During numerical simulation, this integration is performed by the *numerical integration* method to allow for the next model evaluation step.

The switched junctions have the same causal port properties as the regular junctions, but no acausal form of the constitutive relations exists, while it necessarily contains 'if-then-else' statements that can only be written after causality has been assigned.

The algebraic relations can be used to eliminate all the variables that do not represent the state of a storage port or an input variable, thus resulting in a set of ordinary differential equations (ODE) if all storage ports have preferred causality or in a set of differential and algebraic equations (DAE) if there are dependent storage ports.

If the elimination of the algebraic relations is done by hand, the following three intermediate steps are advised:

1) eliminate all variables that are dependent on the identities of junctions (0, 1) and sources ((M)Se, (M)Sf)
2) eliminate all variables that are related by the algebraic port relations of all the ports that are not junction ports and not source ports ((M)R(S), (M)TF, (M)GY)
3) eliminate all variables that are related by the port relations of all the ports that are junction summations (0, 1).
4) if an algebraic loop is present (active arbitrary causality) choose a variable in this loop to write an implicit algebraic relation and solve symbolically if possible. Otherwise the use of an implicit numerical method is required.
5) if present and possible, eliminate a differentiated *state variable* at the right-hand side of the relations symbolically if possible. Otherwise the use of an implicit numerical method is required.

For example, the bond graph in figure 4a contains 10 bonds, 20 equations and 20 variables of which two are state variables, such that 18 variables have to be eliminated. There are 9 identities (2 source and 3+2+2=7 junction ports), 6 multiplications (2x2 transducer + 2 R) and 3 summations (3 junctions) resulting in the 18 necessary algebraic relations. The final result, assuming linearity of the elements, is

$$\frac{df_3}{dt} = \frac{1}{I_1}\left(e(t) - R_1 f_3 - n_1 e_7\right) = -\frac{R_1}{I_1} f_3 - \frac{n_1}{I_1} e_7 + \frac{1}{I_1} e(t) \tag{1}$$

$$\frac{de_7}{dt} = \frac{1}{C_1}\left(n_1 f_3 - \frac{R_2}{r_1}\left(\frac{1}{r_1} e_7 - f(t)\right)\right) = \frac{n_1}{C_1} f_3 - \frac{R_2}{C_1 r_1^2} e_7 + \frac{R_2}{C_1 r_1} f(t) \tag{2}$$

or in matrix form:

$$\frac{d}{dt}\begin{bmatrix} f_3 \\ e_7 \end{bmatrix} = \begin{bmatrix} -\frac{R_1}{I_1} & -\frac{n_1}{I_1} \\ \frac{n_1}{C_1} & -\frac{R_2}{C_1 r_1^2} \end{bmatrix}\begin{bmatrix} f_3 \\ e_7 \end{bmatrix} + \begin{bmatrix} \frac{1}{I_1} \\ \frac{R_2}{C_1 r_1} \end{bmatrix}\begin{bmatrix} e(t) \\ f(t) \end{bmatrix} \tag{3}$$

5.6.7 Linear analysis

5.6.7.a Introduction

Even though it may support a frequently encountered, persistent misapprehension that the port-based approach and its bond graph representation require the restriction that all constitutive relations of the nodes of a bond graph should be linear, this assumption will be made in the next section, but only to show the link between bond graphs and commonly used linear analysis techniques in system dynamics. However, it should be strongly emphasized that much of the linear analysis directly applied to the bond graph representation can be qualitatively generalized to the nonlinear case, as it still provides an insight. At the least, it gives an impression about small-signal behavior near an operating point of a nonlinear system model.

Direct application of the wide range of linear analysis techniques on a bond graph should serve a purpose in the sense that it provides some additional information. If this is not the case, there is no need to change from a conventional model representation already obtained, like a set of linear state equations, into a bond graph representation.

If all constitutive relations of the nodes of a bond graph are assumed to be linear, the bond graph represents a linear system model and each elementary node other than the junctions (and the unit gyrator called *symplectic gyrator*) can be characterized by one parameter (C, I, R, TF, GY) or input(signal) ((M)Se, (M)Sf). In case of (external) modulation, the linear system model becomes time-variant (MR, MTF, MGY). Note that internal modulation causes nonlinearity and cannot occur in the linear case.
Given that a causal, linear bond graph is equivalent with any other linear system representation, it can be used to support all kinds of linear analysis. The conversion of a bond graph into a block diagram, a signal flow graph or a set of differential equations was already discussed. This makes clear that any linear analysis technique that exists for these kinds of models formulations can be directly applied to a causal, linear bond graph as well. In particular transmission matrices and Mason's loop rule can be used to derive transfer functions between a chosen input and a chosen output in case of tree and chain structures. As the identification of signal loops takes place in a bond graph via the causal paths, there is an immediate connection during modeling between the properties of a transfer function and the physical properties. The advantage of applying these techniques directly to the bond graph is that the relation of certain aspects of the linear analysis or the transfer function in particular with the physical structure can be directly observed and used to create or to adapt to desired behavior. This not only supports modeling decisions, but also allows insight in how physical changes can be made to obtain a required transfer.

In particular, an impedance analysis will be discussed, as it provides a means to directly generate port equivalent compositions and decompositions. For linear analysis purposes, it is often useful to write the gain related to a node directly in the bond graph. In order to distinguish this notation from the regular notation of characteristic parameters (:) or generating functions (::) the gains, in which differentiations and integrations are replaced by the Laplace operator s and 1/s respectively, are placed between square brackets ([]).

5.6.7.b Impedance analysis using bond graphs

Note that a port of an element in effort-out causality can be characterized by an impedance, while a port with flow-out causality is best described by an admittance.

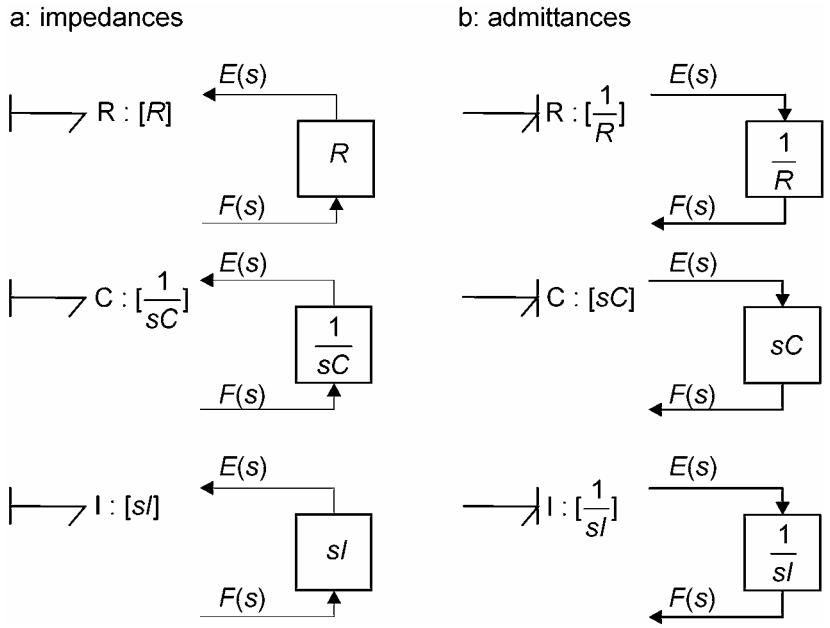


Table 3: Impedance and admittance formulations of 1-port elements and corresponding gains

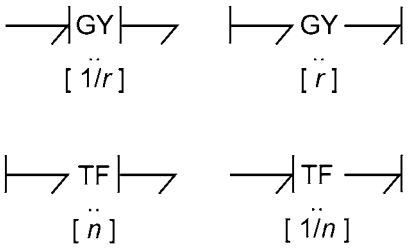


Table 4: Gains 2-port elements in various causal forms

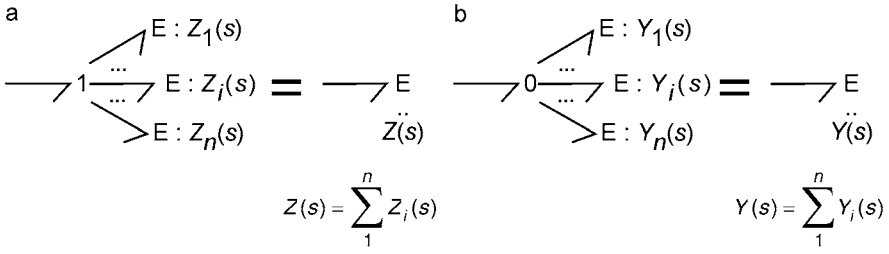


Table 5: Composition rules for junctions and 1-ports

Table 6: Composition rules for 2-ports and 1-ports

Tables 3 and 4 provide listings of the possible gains that characterize the basic elements, both in impedance and in admittance form. Table 5 illustrates that (de-)composition operations involving a 1-junction are best performed in impedance form, while (de-)composition operations involving a 0-junction are best performed in admittance form as this leads to

simple summation operations. Tables 6 and 7 list some elementary (de)composition rules and the results for basic elements respectively.

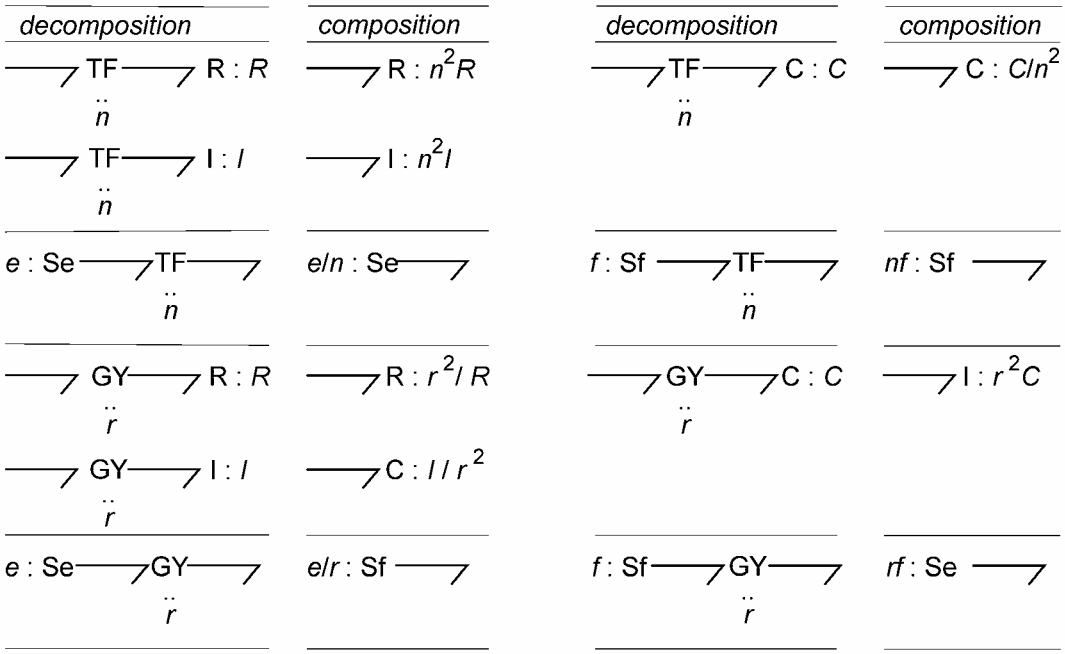


Table 7: (de-)composition rules involving transducers

5.7 Hierarchical modeling

5.7.1 Word bond graphs

Organizing and representing larger system models in a hierarchy can increase efficiency and overview of the modeling process. An example is the so-called word bond graph in which the nodes represent physical components. They can also represent phenomena that may require submodels that contain more than one basic element. Word bond graphs are represented by words or text enclosed by ellipses or circles. These words describe the basic behavior or purpose of a submodel (figure 7a). This notation can also be used to support the first modeling phase in which the relevant physical components in a system are identified without further specification than their dominant behavior. It can be decided later whether other elementary behaviors are also required to obtain a competent model of this physical component.

5.7.2 Multibonds

In many cases multiple bonds connect the nodes of a (word) bond graph. Similar to the notation of multiple signals as ‘double-lined arrows’, it can be useful to represent multiple bond by ‘double-lined half-arrows’ that are called *multibonds*. The *dimension* of a multibond, i.e. the number of constituent bonds, can optionally be written between the two lines of a multibond. Multibonds have initially been introduced as vector bonds. As multibonds are frequently used to represent the coordinates of vectors in planar and spatial mechanisms, while it merely represents a column matrix and *not* a vector in space, this terminology appeared to be highly confusing for a graphical representation and has been abandoned in the early eighties. Apart from the advantages of efficiency and overview, one major disadvantage

of a multibond is that it is not suited to represent the causality except for the situation that the causalities of all constituent bonds are identical. In order to cope with this problem and in order to be able to combine multibond representations with single bond representations the concept of the *direct sum* was introduced, represented by a vertical line perpendicular to the connected bonds. Formally speaking it can be considered a special multiport transformer that is characterized by a unit matrix of which the order of the rows can be changed as to represent a change of order of the participating bonds. In that case, this matrix has to be provided in order to characterize the direct sum, otherwise a unit matrix (no change of order) will be assumed.

5.7.3 Multiport generalizations

A word bond graph adds only one level to the model hierarchy in principle, although multiple layers are possible if physical subcomponents can be identified. However, complex models also require different layers at the conceptual level. This requires multiport generalizations of the nodes.

5.7.3.a Sources

By definition a multiport requires that its ports are interrelated. This means that the sources cannot be combined into a multiport due to the nature of a source, i.e. no dependency on the conjugate variables, but source *arrays* can be used (cf. subsection 5.7.3.f).

5.7.3.b Multiport storage elements

The storage elements can be generalized into a multiport in which the number of ports is equal to the number of *energy states*. The energy function of these states can be used to generate the constitutive relations of this multiport similar to the Gibbs relation in thermodynamics or to the Hamiltonian description of mechanical systems. It is obvious that this makes this notation and approach an ideal instrument to establish a link between these two huge scientific areas. The constitutive relation has to satisfy the *Maxwell reciprocity condition* (in Hamiltonian mechanics this is expressed as the energy being a so-called closed two-form) in order to satisfy the energy conservation principle. This condition is also called Maxwell symmetry as it requires the symmetry of the Jacobian of the constitutive relations.
However, a multiport storage element adds the potential of a new behavior that is not represented by one of the basic elements, viz. *reversible transformation* by cycle processes as opposed to the instantaneous reversible transformation represented by a transformer or a gyrator. From a conceptual design point of view, it is worthwhile to note that, in principle, instantaneous power *transduction* between domains does not ‘exist’ in principle (e.g. *passive* DC transformers cannot be realized, often rotating parts or cycling ‘working fluids’ are required to construct continuous power transducers), but can only be approximated by relatively fast cycles or cycles in which the storage can be neglected (e.g. intermittent elastic storage in the touching gears of a gear box).
Another important observation with respect to multiport storage elements is that the integral causality of the ports corresponds to a generating function that is equal to the energy. If an integral causality of a port is changed into a differential one, this corresponds to replacing the (extensive) *energy state* by its (intensive) conjugate variable (partial derivative of the energy with respect to the conjugate state). This, in turn, corresponds mathematically to a *Legendre transform* of a function of multiple variables. *Legendre transforms* are not only often used in thermodynamics when the conjugate variable of a state (intensive state, effort) can be assumed constant (e.g. *free energy* in case of constant temperature, *enthalpy* in case of constant pressure, *Gibbs free energy* in case of constant temperature and pressure), but also in

mechanics where the dual nature of the *position* variable, i.e. *energy state* and *configuration state*, has led to a preference for the *position* and its derivative, the *velocity*, instead of the true extensive *energy states*: *position* and *momentum*. As a consequence, the *Hamiltonian* (kinetic energy (T) + potential energy (V)) is often Legendre transformed into the *Lagrangian* (kinetic *co*-energy (T^*) - potential energy (V)), although this generally does not lead to equations that are optimally suited for numerical simulation. This wide field of research is still under study, but many important results have been obtained that appear not yet generally known.
A final observation to be mentioned is that in the linear case a multiport storage element can always be decomposed into some one-port storage elements and a power continuous junction structure (GJS). If the number of independent parameters required to characterize the multiport or n-port, viz. $n+(n^2-n)/2 = n(n+1)/2$, is equal to the number of parameters in the decomposition, the decomposition is called a *canonical decomposition*. Note that decompositions depend on the causality of the ports. Reversibly, a bond graph that only contains storage elements and a non-modulated (except state modulation by the states of the participating storage elements) junction structure with open ports can be composed into one multiport storage element. There are only two types of canonical decompositions of a linear two-port storage element: three linear storage elements connected by an SJS (direct or immediate canonical decomposition) or two linear storage elements connected by a GJS with only one linear transducer (congruence canonical decomposition).

5.7.3.c Multiport resistors

The resistive port of an *irreversible transducer* can also be generalized in multiport form. The *Jacobian* of its relations has to be symmetric as only this symmetric part contributes to the entropy production. A potential non-symmetric Jacobian can always be separated into a symmetric part that can be represented by a resistive port and an antisymmetric part that can be represented by the multiport generalization of a gyrator, which is a power continuous junction structure element. This issue has been a source of conflict in thermodynamics: in the thirties Onsager introduced firstly his Onsager symmetry for the relation between generalized forces (efforts) and generalized fluxes (flows), i.e. for what is now called a multiport resistor; next Casimir, inspired by a discussion with Tellegen, who introduced the gyrator in electrical engineering in the late fourties, extended this by showing that in some cases there is an antisymmetric contribution. Finally, Truesdell showed that a transformation of the conjugate variables can always symmetrize these relations, which corresponds to changing the 'port of view' in a bond graph (figure 6). There exist (canonical) decompositions of multiport R(S) elements similar to those of the storage elements but the constraint on linearity is much less severe.

Figure 6: Symmetrizing a dissipative multiport ($R_s + R_a$) into R_s by changing the 'port of view' ($B \rightarrow A$)

5.7.3.d Multiport transducers

The elementary two-port elements, TF and GY, can be generalized in a straightforward manner by changing the scalar conjugate variables in their relations into column matrices. The scalar transduction ratio then becomes a transduction matrix. In case of a multiport transformer, the matrix itself describes the flow-relation and its transpose the effort relation, as can be derived from power continuity.
In case of the gyrator there is simply one relation between efforts and flows that is characterized by the gyration matrix. This makes clear that the format of the constitutive

relation of a gyrator is similar to that of a resistive port, even though the gyrator belongs to the (generalized) junction structure. It can thus be seen as the antisymmetric counterpart of a symmetric R-port too (cf. figure 6).
The causality constraints of the multiport transformer are related to the (partial) invertibility of the transformation matrix. If the dimension of the inward multibond is not equal to the dimension of the outward multibond, the matrix is not square and singular as a result. This means that the causality of the multibonds cannot be inverted. However, it may still be possible to invert the constitutive matrix partially. This requires a mixed causality of the multibonds and accordingly the use of the direct sum.

5.7.3.e Multiport components

The port relations of arbitrary multiports can be used as a starting point for decomposing them into basic elements. The nature of the variables plays an important role: constitutive relations of true power ports should be formulated in terms of efforts and flows or their time integrals (*energy states*). If the latter case occurs this indicates that the port should at least contain one storage element. Depending on the shape of this relation other elements may be needed to represent the corresponding behavior. For instance, the presence of a cycle demonstrates the presence of either another coupled storage port, or a form of hysteresis caused by a resistive phenomenon.

5.7.3.f Arrays

In the multibond notation it is sometimes helpful to be able to collect a number of the same symbols, even if they are not directly related. For instance, a collection of 1-port I-type elements representing the storage of momentum of a body in three independent coordinate directions has no power relation (at least, not in the *inertial frame*), but should conceptually be connected. The concept of an array of bonds or elements, represented by underlining the corresponding symbol is used. Nesting (arrays of arrays, etc.) is possible, but only advised as long as it enhances insight. For instance, three *n*-dimensional multibonds connected to an (*n*-dimensional) junction array (each bond connects only to the junction in the array matching its index) has a different meaning from three *n*-dimensional multibonds connected to a single junction (all bonds connected to one and the same junction), even though the difference in notation is just the underlining of the junction symbol. The first is often encountered in models of planar and spatial mechanisms, while the second is encountered in models of chemical reactions for example.

6 Port-based modeling and simulation of dynamic behavior of physical systems in terms of bond graphs: a simple example

The model structure of a simple *servo system* (see Servo Control Design) is generated in order to give an impression of the port-based approach and the feedback on modeling decisions provided by the causal analysis. First a word bond graph is drawn at the component level, combined with a block diagram representation of setpoint, controller and closed loop (figure 7a). This gives an impression of the important domains and the corresponding variables of interest. Next the components are replaced by the nodes of a bond graph that represent the dominant behavior of each of the components (figure 7b). The causality shows that, apart from the dynamics of the controller and the integration in the position sensor the drive system model has no dynamics: the imposed voltage directly determines the servo speed (1^{st} order system). In order to add some dynamic behavior, the resistance and inductance of the motor circuit, the friction and inertia of the rotor are added as well as the inertia of the

load (figure 7c). The causality not only shows that the rigid connection between the rotor inertia and the load inertia makes them dependent, but also that the inductance of the motor circuit forms a second order loop (causal path) with the mechanical inertia (rotor & load) via the gyrator (3^{rd} order system). Figure 7d demonstrates that modeling the torsion of the drive system resolves the dependency between rotor and load inertia, but creates a new second order loop (5^{th} order system). Figure 7e shows that changing from a voltage control of the motor to current control not only suppresses its electrical time constant, but also the second order loop between inertia and inductance via the gyrator.

Figure 7a: Word bond graph of a simple servo system

Figure 7b: Bond graph of the dominant behaviors

Figure 7c: Bond graph of the dominant behaviors and some important dynamics

Figure 7d: Addition of the torsion of the drive system resolves the dependency between rotor and load inertia

Figure 7e: Current-control of the motor suppresses the electrical time constant as well as the second order loop via the GY

Note that figures 7a-e are all screen dumps of models that can directly be simulated when relevant parameters are selected.
The information of all these steps supports the modeling process, depending on the problem context.

The introduction to bond graph concepts and notation in previous sections has already discussed many links between the representation and the modeling process. It cannot be sufficiently emphasized that modeling is a decision process that is different each time, but which can be supported by looking for conceptual structure based on universal principles as well as a direct link with computational issues, which provides direct feedback on modeling decisions. The bond graph notation supports this due to its domain independence and its ability to represent conceptual and computational information simultaneously. A true understanding of these features is only obtained by sufficient practicing.

7 Future trends

The following general future trends in bond graphs and port-based modeling can be distinguished:

1) continuous improvement and extension of computer support for bond graph representation, analysis and generation of numerical simulation models
2) mathematical formalization (port-Hamiltonian systems) of all aspects of the approach thus establishing a relation with other model views and analysis techniques
3) extension of port-interfaces to other submodel descriptions like wave-scattering variables and finite elements
4) heuristic tools that support the port-based modeling decision process as well as the settings of the numerical analysis
5) support of knowledge management in order to store and use relevant information about the problem context, model performance, etc.

6) use of the port-based approach for *co-simulation*

Bibliography

A full bond graph bibliography can be found at www.ece.arizona.edu/~cellier. Some of the seminal publications are:

Books and special issues

Altmann A. (1982). *Interdisziplinäre Systemanalyse, eine Strukturalgebra der Bonddiagramme*, Springer-Verlag, Berlin. [Early attempt to a mathematical formalization of bond graphs]

Blundell A.J. (1982), *Bond Graphs for Modelling Engineering Systems*, Ellis Horwood Publishers, Chichester, U.K., and Halsted Press, New York, 151p. [Another textbook on bond graph modeling; uses e- and f- (or equivalent domain dependent variable names) instead of 0- and 1-junctions]

Breedveld P.C. (1984). *Physical Systems Theory in terms of Bond Graphs*, ISBN 90-9000599-4, (distr. by author). [Introduction of the Generalized Bond Graph concept in a Multibond notation in particular used for thermofluid systems]

Breedveld P.C., Borne P., Tsafestas S. and Dauphin-Tanguy G. (eds.). (1989). *IMACS Annals of Computing and Applied Mathematics, Vol. 3: Modeling and Simulation of Systems*, J.C. Baltzer A.G., Basel. [Collection of independent chapters by various authors on bond graph related research]

Breedveld P.C. (ed.) (1991). *Current topics in Bond Graph Related Research*, J. Franklin Inst., Vol. 328, No.:5/6. [Third in a series of special issues with a high impact containing a large collection of papers on bond graph related research]

Breedveld P.C. and Dauphin-Tanguy G. (eds.) (1992). *Bond graphs for Engineers*, IMACS Transaction Series, Elsevier Science Publishers, Amsterdam, ISBN 0 444 89707 0. [Collection of papers on bond graph modeling and simulation]

Breedveld P.C. and Amerongen J. van (1994). *Dynamic Systems: Modeling and simulation using bond graphs*, part 1-4, ISBN 90 358 1302 2 (in Dutch;, second, modified edition in English to appear in 2004 as a textbook), Open University, Heerlen, Netherlands. [Extensive set of introductory lecture notes]

Callen H.B. (1960). Thermodynamics, Wiley, New York. [An energy-based, systematic approach to thermodynamics making use of the concept of the Legendre transform; good basis for the analysis of storage multiports.]

Cellier F.E. (1991). *Continuous System Modeling*, Springer-Verlag, New York, ISBN 0-387-97502-0, 755p. [Textbook on modeling for simulation based on the port-based approach]

Dauphin-Tanguy G., Borne P., Tsafestas S. and Breedveld P.C. (eds.) (1989) *IMACS Annals of Computing and Applied Mathematics*, Vol. 4, J.C. Baltzer A.G., Basel,.

Dixhoorn J.J. van and Evans F.J. (Eds.) (1974). *Physical Structure in Systems Theory: Network Approaches to Engineering and Economics*, Academic Press, London, 305p. [Seminal book on physical system modeling; collection of chapters by various authors]

Dixhoorn J.J. van and Karnopp D.C. (eds.) (1985). *Physical Structure in Modelling*, Special Issue of the J. Franklin Inst., Vol. 319, No. 1/2. [Second in a series of special issues with a high impact containing a large collection of papers on bond graph related research]

Dransfield P.D. (1981). *Hydraulic Control Systems - Design and Analysis of Their Dynamics*, Lecture Notes in Control and Information Sciences in: A.V. Balakrishnan and M. Thoma,

(eds.), Springer-Verlag, Berlin, Vol.33, 225p. [Port-based approach to hydraulic (control) systems]

Hogan N.J. and Breedveld P.C. (2002), *The Physical Basis of Analogies in Physical System Models*, in: Robert H. Bishop, ed., The Mechatronics Handbook, CRC Press, Boca Raton (FA), USA, pp. 15-1 - 15-10, ISBN 08 493 00665. [An attempt based on arguments of various nature to resolve the controversy between the force-voltage analogy and the force-current analogy]

Karnopp D.C. and Rosenberg R.C. (1968) *Analysis and Simulation of Multiport Systems - The Bond Graph Approach to Physical Systems Dynamics*, M.I.T. Press, Cambridge, Mass. [Seminal book on bond graph modeling and simulation]

Karnopp D.C. and Rosenberg R.C. (1974). *System Dynamics: A Unified Approach*, John Wiley, New York, 1974. [Course text on System Dynamics from a port-based perspective]

Karnopp D.C., Pomerantz M.A., Rosenberg R.C. and Dixhoorn J.J. van (eds.) (1979) *Bond Graph Techniques for Dynamic Systems in Engineering and Biology*, Special issue of the Journal of the Franklin Institute, Vol. 308, No. 3. [First in a series of special issues with a high impact containing a large collection of papers on bond graph related research]

Karnopp D.C., Margolis D.L. and Rosenberg R.C. (1990). *System Dynamics: A Unified Approach - 2nd Edition*, John Wiley, New York. [Second, extended edition of the successful 1974 textbook]

Paynter H.M. (1961). *Analysis and Design of Engineering Systems*, M.I.T. Press, Cambridge, Mass., 1961. [The first book on bond graphs (and much more) by their inventor, unfortunately out of print]

Paynter H.M. (1992). *An Epistemic Prehistory of Bond Graphs*, in: P.C. Breedveld and G. Dauphin-Tanguy, eds., Bond Graphs for Engineers, Elsevier, Amsterdam, pp.3-17 [Interesting historic perspective by the inventor himself].

Rosenberg R.C. (1965). *Computer-Aided Teaching of Dynamic System Behavior,* Ph.D. Dissertation, M.I.T. [Development of the first port-based computer simulation tool]

Rosenberg R.C. (1974). *A User's Guide to ENPORT-4*, John Wiley, New York. [Manual of the first port-based computer simulation tool]

Rosenberg R.C. and Karnopp D.C. (1983). *Introduction to Physical System Dynamics*, McGraw-Hill, New York. [Course text for the undergraduate level]

Schnakenberg J. (1981). *Thermodynamics Network Analysis of Biological Systems*, 2nd Corrected and Updated Edition, Universitext, Berlin,. [Rather abstract text, in particular aimed at thermodynamical and (bio)chemical system models]

Thoma J.U. (1975). *Introduction to Bond Graphs and Their Applications* Pergamon Press, Oxford. [Course text with special emphasis on thermal and hydraulic systems; uses p- and s-in stead of 0- and 1-junctions]

Thoma J.U. (1989). *Simulation by Bondgraphs - Introduction to a Graphical Method*, Springer-Verlag, New York. [Textbook: introduction for the undergraduate level focused on generating simulation models]

Truesdell C. (1969). *Rational Thermodynamics*, McGraw-Hill, New York. [Contains an interesting view on Onsager symmetry, cf. subsection 5.7.3.c]

Wellstead P.E. (1979). *Introduction to Physical System Modelling*, Academic Press, London. [Comparision of the use of network methods (linear graphs), variational techniques (Lagrange) and bond graphs in physical system modeling]

Papers

Allen R.R. (1981) *Dynamics of Mechanisms and Machine Systems in Accelerating Reference Frames*, Trans. of the ASME, J. of Dynamic Systems Measurement and Control, 103(4), pp.395-403. [Introduces the gyristor as a conceptual element]

Amerongen J. van and Breedveld P.C. (2002). *Modelling of Physical Systems for the Design and Control of Mechatronics Systems* in: IFAC Professional Briefs, published in relation to the 15th triennial IFAC World Congress, International Federation of Automatic Control (http://www.ifac-control.org), Laxenburg, Austria, pp. 1-56. [Survey that introduces the port-based approach via direct simulation of iconic diagrams]

Atlan H. and Katzir-Katchalsky A. (1973) *Tellegen's Theorem for Bond Graphs and Its Relevance to Chemical Networks*, Curr. Mod. Biol., 5, pp.55-65. [Discovery of the port-based approach by thermodynamicists]

Auslander D.M., (1968) *Distributed System Simulation With Bilateral Delay-Line Models*, Trans. of the ASME, J. of Basic Engineering, 90(2), pp.195-200. [A kind of wave scattering approach to distributed systems]

Auslander D.M., Oster G.F., Perelson A.S. and Clifford G. (1972). *On Systems With Coupled Chemical Reaction and Diffusion*, Trans. of the ASME, J. of Dynamic Systems Measurement and Control, 94(3), pp.239-248. [Port-based approach applied to coupled reaction-diffusion networks]

Beaman J.J. and Breedveld P.C. (1988). *Physical Modeling with Eulerian frames and Bond Graphs*, Trans. ASME, J. of Dyn. Syst., Meas. & Control, Vol. 110, No. 2, pp. 182-188. [Port-based modeling of compressible fluid flow]

Bidard C. (1991). *Kinematic Structure of Mechanisms: A Bond Graph Approach*, J. of the Franklin Institute, 328(5/6), pp.901-915. [Thorough study of a synthesis between a structured description of kinematics and port-based models of the dynamics of rigid body systems]

Bonderson L.S. (1975). *Vector Bond Graphs Applied to One-Dimensional Distributed Systems*', Trans. of the ASME, J. of Dynamic Systems Measurement and Control, 97(1), pp.75-82. [First use of a rudimentary multibond notation]

Breedveld P.C. (1979). *Irreversible Thermodynamics and Bond Graphs: A synthesis with some practical examples*, MSc. Thesis (in Dutch), No.1241.2149, Department of Electrical Engineering, University of Twente, Enschede, Netherlands. [First introduction of the symplectic gyrator and generalized bond graphs (then still called thermodynamic bond graphs)]

Breedveld P.C. (1981). Thermodynamic Bond Graphs: a new synthesis', Int. J. of Modeling and Simulation, Vol. 1, No. 1, pp. 57-61, Acta Press, Anaheim (Cal.), 1981. [Condensed English version of [Breedveld, 1979]]

Breedveld P.C. (1982). *Thermodynamic Bond Graphs and the problem of thermal inertance*, J. Franklin Inst., Vol. 314, No. 1, pp. 15-40. [Resolution of the paradoxal concept of the thermal I-element that seems to follow from the mechanical framework of variables]

Breedveld P.C. (1982), *Proposition for an unambiguous Vector Bond Graph notation*, Trans. ASME, J. of Dyn. Syst., Meas. & Control, Vol. 104, No. 3, pp. 267-270. [Definition of the vector bond notation, later called multibond notation]

Breedveld P.C. (1984). *A Bond Graph Algorithm to determine the Equilibrium State of a System*, J. Franklin Inst., Vol. 318, No. 2, pp. 71-75. [Documentation of a useful procedure]

Breedveld P.C. (1984) *Essential Gyrators and Equivalence Rules for 3-port Junction Structures*, J. Franklin Inst., Vol. 318, No. 2, pp. 77-89. [A study on how essential gyrators

are contained in junction structures and how equivalence rules can be used to eliminate bond loops]

Breedveld P.C. (1984). *Decomposition of Multiport Elements in a Revised Multibond Graph Notation*', J. Franklin Inst., Vol. 318, No. 4, pp. 253-273. [Decomposition and composition of multiport elements, in particular canonical decompositions]

Breedveld P.C. (1985). *Multibond Graph Elements in Physical Systems Theory*, J. Franklin Inst., Vol. 319, No. 1/2, pp. 1-36. [Chapter two of [Breedveld, 1984] listed under 'books' in a more accessible form]

Breedveld P.C. (1986). *A definition of the multibond graph language*, in 'Complex and Distributed Systems: Analysis, Simulation and Control', Tzafestas, S. and Borne, P., eds., Vol. 4 of 'IMACS Transactions on Scientific Computing', pp. 69-72, North-Holland Publ. Comp., Amsterdam. [Refined definition of the multibond graph notation]

Breedveld P.C. (1991) An alternative formulation of the state equations of a gas', Entropie, Vol. 164/165, pp. 135-138, ISSN 0013 9084. [Motivation and derivation of the uncommon integral causal form of a three-port C representing storage in a gas]

Breedveld P.C. and Hogan N.J. (1994). *Multibond-graph Representation of Lagrangian Mechanics: The Elimination of the Euler Junction Structure*, Proc. IMACS 1. MathMod Vienna, Feb. 2-4, Technical University Vienna, Austria, I.Troch and F. Breitenecker (Eds.), Vol. 1, pp. 24-28. [Demonstration that the apparent essential gyrator in an EJS can be eliminated by transformation to the generalized coordinates]

Breedveld P.C. (1995). *Exhaustive decompositions of linear two-ports*, Proc. SCS 1995 International Conference on Bond Graph Modeling and Simulation (ICBGM'95), SCS Simulation Series Vol. 27, No.1, January 15-18, Las Vegas, edited by F.E. Cellier and J.J. Granda, pp. 11-16, ISBN 1-56555-037-4. [Proof that the immediate and congruence canonical decompositions are the only canonical decompositions of linear two-ports.]

Breedveld P.C. (1996). *The context-dependent trade-off between conceptual and computational complexity illustrated by the modeling and simulation of colliding objects*, Proc. Computational Engineering in Systems Applications '96 IMACS/IEEE-SMC Multiconf., July 9-12, Lille, France, P. Borne et al. (eds.), Late Papers Vol., pp. 48-54. [Demonstration that the concept of a 'hybrid model' is often applied causing unnecessarily complex models, while a careful observation of the physics point out a much simpler solution]

Breedveld P.C. (1999) *Insight in rigid body motion stability via an alternative for the Eulerian Junction Structure*, Proc. SCS International 1999 Western MultiConference, January 17 - 20, San Francisco, Cal., Simulation Series Vol. 31, No.1, pp. 269-274, ISBN 1-56555-155-9. [Proof that the EJS is a non-canonical decomposition that does not contain a gyrator in an essential way thus resolving a longstanding paradox]

Breedveld P.C. (2000). *An Alternative Model for Static and Dynamic Friction in Dynamic System Simulation*, 1st IFAC conference on Mechatronic Systems, pp. 717-722, Darmstadt, Germany. [Introduction of a port-based friction model that allows the description of static friction without changing causality and without creating a numerically stiff system of equations]

Breedveld P.C. (2000) *Constitutive Relations of Energy Storage in a Gas in Preferred Integral Causality*, Proceedings IECON-2000 IEEE International Conference on Industrial Electronics, Control and Instrumentation, 21st Century Technologies and Industrial Opportunities, October 22 - 28, Nagoya Congress Center, Nagoya, Aichi, JAPAN, pp. 1580-1585. [Conditions for being able to write constitutive relations of a gas in integral causal form and resolving the problem of finding the initial conditions]

Breedveld P.C. (2001) *Paynter's Veridical State Equation in Integral Causal Form*, Proc. SCS International 2001 Western MultiConference (International Conference on Bond Graph Modeling and Simulation, ICBGM 01), Phoenix, Arizona, January 7–11, pp. 27-32. [Derivation of the integral form of Paynter's Veridical State Equation that can be much closer fitted to experimental data than the ideal gas or van-der-Waals gas relations]

Breunese A.P.J. and Breedveld P.C. (1996). *Analysis of Equation Submodels*, Mathematical Modeling of Systems, Vol. 2, No. 2, pp. 134-156. [Study that lied the basis for an efficient automatic generation of a computable set of equations from a port-based computer input]

Brown F.T. (1972) *Direct Application of the Loop Rule to Bond Graphs*, Trans. of the ASME, J. of Dynamic Systems Measurement and Control, 94(3), pp.253-261. [Famous and frequently cited paper on how an already existing algorithm can be successfully applied to a bond graph while enhancing insight in the relation between a (desired) transfer function and the physics of the system]

Busch-Vishniac I.J. and Paynter H.M. (1991). *Bond Graph Models of Acoustical Transducers*, J. of the Franklin Institute, 328(5/6), pp.663-673 [A study of transducers in terms of multiport (storage) elements].

Casimir H.B.G. (1945). *On Onsager's Principle of Microscopic Reversibility*, Rev. Mod. Phys., Vol. 17, pp. 343-350. [Historic paper in which Casimir shows when Onsager symmetry breaks down, cf. subsection 5.7.3.c]

Cellier F.E. (1992). *Hierarchical Non-Linear Bond Graphs: A Unified Methodology for Modeling Complex Physical Systems*, Simulation, 58(4), pp.230-248. [Paper demonstrating the advantages of a port-based approach to a wider simulation audience]

Colgate J.E. and Hogan N.J. (1988) *Robust Control of Dynamically Interacting Systems*, International J. of Control, 48(1), pp.65-88. [Port-based approach to the control of dynamically interacting systems]

Dijk J. van, and Breedveld P.C. (1991). *Simulation of system models containing zero-order causal paths - part I: Classification of zero-order causal paths*, J. Franklin Inst., Vol. 328, No.:5/6, pp. 959-979. [Classification of causal paths with algebraic loop gain that lead to DAE's]

Dijk J. van and Breedveld P.C. (1991). *Simulation of system models containing zero-order causal paths - part II: Numerical implications of class-1 zero-order causal paths*, J. Franklin Inst., Vol. 328, No.: 5/6, pp. 981-1004. [Numerical solution of DAE's that result from models with zero-order causal paths]

Dijk J. van and Breedveld P.C. (1993). *The Structure of the Semi-state Space Form Derived from Bond Graphs*, Proc. 1993 Western Simulation Multiconference on Bond Graph Modeling (ICBGM '93), SCS Simulation Series, Vol. 25, no.2, J.J. Granda & F.E. Cellier, eds., La Jolla, Cal., Jan. 17-20, ISBN: 1-56555- 019-6, pp. 101-107. [Paper demonstrates that a bond graph model of a constrained system commonly leads to a numerically solvable DAE system of index one and seldomly to index two, but not higher.]

Diller K.R., Beaman J.J., Montoya J.P. and Breedveld P.C. (1988). *Network Thermodynamic Modeling With Bond Graphs for Membrane Transport During Cell Freezing Procedures*, Trans. ASME, J. of Heat Transfer, Vol. 110, pp. 938-945. [Application of the generalized bond graph approach to a membrane transport case study]

Dixhoorn J.J. van (1972). *Network Graphs and Bond Graphs in Engineering Modelling*, Annals of Systems Research, 2, pp. 22-38. [Seminal paper about the use of bond graphs in engineering and education]

Dransfield P.D. (1975). *Power Bond Graphs - Powerful New Tool for Hydraulic System Design*, J. of Machine Design, 47(25), pp.134-138. [Introduction to bond graphs focused on applications in hydraulics]

Golo G., Breedveld P.C., Maschke B.M. and Schaft A.J. van der. (2001). *Reduction of Constraints in Generalized Bond Graphs*, Proc. SCS International 2001 Western MultiConference, Phoenix, Arizona, January 7–11, pp. 313-318. [Novel technique to reduce constraints in systems represented by GBG's]

Golo G., Breedveld P.C., Maschke B.M. and Schaft A.J. van der (2000). *Input Output representation of Dirac structures and junction structures in bond graphs*', Mathematical Theory of Networks and Systems, June 19-23, Perpignan, France. [Paper explaining the bond graph junction structure concept in terms of a Dirac structure]

Golo G. (2002). *Interconnection Structures in Port-bases modelling: Tools for analysis and simulation*, Twente University Press, ISBN 9036518113, 229 pages. [Mathematical formalization of bond graphs with a new and robust approach to causal analysis]

Hogan N.J. (1985), *Impedance Control: An Approach to Manipulation: Part I – Theory, Part II – Implementation, Part III – Applications*, Trans. of the ASME, J. of Dynamic Systems Measurement and Control, 107(1), pp.1-7, pp.8-16, pp.17-24. [Seminal papers on the impedance control philosophy]

Hogan N.J. and Breedveld P.C. (1999). *On the physical basis of the analogies used in network models of physical systems*, Proc. SCS International 1999 Western MultiConference, January 17-20, San Francisco, Cal., Simulation Series Vol. 31, No.1, pp. 96-104, ISBN 1-56555-155-9. [This paper tries to resolve the paradoxal controversy between the force-voltage analogy and the force-current analogy]

Hrovat D. and Margolis D.L. (1981). *An Experimental Comparison Between Semi-Active and Passive Suspensions for Air-Cushion Vehicles*, International J. of Vehicle Design, 2(3), pp.308-321. [This paper demonstrates how the port-based approach leads to new engineering solutions like semi-active suspension systems]

Hrovat D. and Tobler W.E. (1985). *Bond Graph Modeling and Computer Simulation of Automotive Torque Converters*, J. of the Franklin Institute, 319(1/2), pp.93-114. [One of the first application papers by automotive engineers]

Joseph B. J. and Martens H.R. (1974). *The Method of Relaxed Causality in the Bond Graph Analysis of Nonlinear Systems*, Trans. of the ASME, J. of Dynamic Systems Measurement and Control, 96(1), pp.95-99. [Seminal paper on numerical issues that would obtain its full impact only one to two decades later]

Karnopp D.C. (1969). 'Power-Conserving Transformations: Physical Interpretations and Applications Using Bond Graphs', J. of the Franklin Institute, 288(3), pp.175-201. [Seminal paper of a bond graph pioneer on the role of position modulated multiport transformers in mechanical system models]

Karnopp D.C. (1978), *The Energetic Structure of Multibody Dynamic Systems*, J. of the Franklin Institute, 306(2), pp.165-181. [Key paper on multibody system models]

Karnopp D.C. and Rosenberg R.C. (1970). *Application of Bond Graph Techniques to the Study of Vehicle Drive Line Dynamics*, Trans. of the ASME, J. of Dynamic Systems Measurement and Control, 92(2), pp.355-36. [Early application study in a typical multidomain area]

Lebrun M. (1985). The Use of Modal Analysis Concepts in the Simulation of Pipeline Transients', J. of the Franklin Institute, 319(1/2), pp.137-156. [Port-based approach to modal analysis of pipeline models]

Linkens D.A. (1990). *Bond Graphs for an Improved Modelling Environment in the Life Sciences*, IEE Digest No.1990/063, pp.3/1-4. [The paper emphasizes the universal power of representing relations by a-causal bi-lateral signal flows between ports in stead of a priori causal input-output models]

Margolis D.L. (1985). *A Survey of Bond Graph Modeling for Interacting Lumped and Distributed Systems*, J. of the Franklin Institute, 319(1/2), pp.125-135. [A paper by a key author in this field, the title speaks for itself…]

Maschke B.M., Schaft A.J. van der and Breedveld P.C. (1992), *An intrinsic Hamiltonian formulation of network dynamics: non-standard Poisson structures and gyrators*, J. Franklin Inst., Vol. 329, No. 5, pp. 923-966. [One of the first papers to introduce the geometric interpretation of the port-based approach]

Maschke B.M., Schaft A.J. van der and Breedveld P.C. (1995). *An intrinsic Hamiltonian formulation of dynamics of LC-circuits*, Trans. IEEE on Circuits and Systems, Vol. 42, No. 2, pp. 73-82. [Application of the geometric interpretation of the port-based approach to LC-circuits]

Onsager L. (1931). *Reciprocal Relations in Irreversible Processes I & II*, Phys. Rev. Vol. 37, pp. 405-426 & 2265-2279. [Introduction of Onsager symmetry, cf. subsection 5.7.3.c]

Oster G.F. and Perelson A.S. (1974). *Chemical Reaction Networks*, IEEE Trans. Circuits and Systems, 21, pp.709-721. [This paper demonstrates that the port-based approach also applies to chemical reactions]

Oster G.F., Perelson A.S. and Katzir-Katchalsky A. (1973) *Network Thermodynamics: Dynamic Modelling of Biophysical Systems*, Quarterly Reviews of Biophysics, 6(1), pp.1-134. [Introduction of a network approach to thermodynamics, inspired by bond graphs]

Paynter H.M. (1959), *Hydraulics By Analog - An Electronic Model of a Pumping Plant*, J. Boston Society of Civil Engineering, July 1959, pp.197-219. [Historically interesting paper by the inventor of bond graphs in the year he invented the junctions]

Paynter H.M. (1969) *Bond Graphs and Diakoptics*, The Matrix Tensor Quarterly, 19(3), pp.104-107. [Relation between the port-based approach and Gabriel Kron's Diakoptics]

Paynter H.M. (1970) 'System Graphing Concepts', Instruments Control Systems, 43(7), pp.77-78 [Discussion of the graphical representation of the port-based approach to systems]

Paynter H.M. (1972). *The Dynamics and Control of Eulerian Turbomachines*, Trans. of the ASME, J. of Dynamic Systems Measurement and Control, 94(3), pp.198-205. [Application of the modulated gyrator to model turbomachines]

Paynter H.M. (1986) Waves-Scatter Bond Graphs for Electroacoustic Systems', J. of the Acoustical Society of America, 80, Supplement 1, p.S6. [The inventor of bond graphs discusses an alternative choice of power conjugate variables]

Paynter H.M. and Beaman J.J. Jr. (1991). *On the Fall and Rise of the Circuit Concept*, J. of the Franklin Institute, 328(5/6), pp.525-534. [Historical overview of some key developments in the field]

Paynter H.M. and Busch-Vishniac I.J. (1989) *Wave-Scattering Approaches to Conservation and Causality*, J. of the Franklin Institute, 358(3), pp.295-313. [Paper that exploits that wave-scattering variables can serve as power conjugate variables, despite the fact that their relation with power is not a product]

Perelson A.S. (1975). *Bond Graph Sign Conventions*, Trans. of the ASME J. of Dynamic Systems Measurement and Control, 97(2), pp.184-188. [This paper demonstrates that unoriented bond graphs (still common at that time) can be meaningless]

Perelson A.S. (1975). *Bond Graph Junction Structures*, Trans. of the ASME J. of Dynamic Systems Measurement and Control, 97(2), pp.189-195. [One of the first attempts to give a mathematically precise definition of a junction structure that emphasizes the importance of positive orientation and causality in the analysis of junction structures, in particular those containing bond loops]

Perelson A.S. and Oster G.F. (1975). *Chemical Reaction Dynamics, Part II. Reaction Networks*, Archives of Rational Mechanical Analysis, 57(1), pp.31-98. [Seminal paper that includes chemical reaction dynamics in the port-based approach]

Pol F.C.M. van de, Breedveld P.C. and Fluitman J.H.J. (1990). *Bond-Graph Modeling of an Electro-Thermo-Pneumatic Micropump*, Proc. 2nd Worksh. Micromachining, Micromechanics & Microsystems, Berlin, Nov. 26-27. [Port-based modeling of a multidomain application]

Rosenberg R.C. (1993). *Reflections on Engineering Systems and Bond Graphs*, Trans. of the ASME, J. of Dynamic Systems Measurement and Control, 115(2B), pp.242-251. [A bond graph pioneer discusses the key insights in the dynamics of engineering systems that can be obtained from a bond graph approach]

Rosenberg R.C. and Karnopp D.C. (1972). *A Definition of the Bond Graph Language*, Trans. of the ASME, J. of Dynamic Systems Measurement and Control, 94(3), pp.179-182. [One of the first attempts to standardize the bond graph notation]

Sharon A., Hogan N.J. and Hardt D.E. (1991), 'Controller Design in the Physical Domain', J. of the Franklin Institute, 328(5/6), pp.697-721. [This paper demonstrates that important role of physical interpretation in controller design]

Stein J.L. (1993). *Modeling and State Estimator Design Issues for Model-Based Monitoring Systems*, Trans. of the ASME, J. of Dynamic Systems Measurement and Control, 115(2B), pp.318-327. [Application of port-based modeling to model-based monitoring]

Tiernego M.J. L. and Dixhoorn J.J. van (1979). *Three-Axis Platform Simulation: Bond Graph and Lagrangian Approach*, J. of the Franklin Institute, 308(3), pp.185-204. [One of the first comparisons between a port-based approach and a Lagrangian approach to spatial body dynamics]

Top J.L., Akkermans J.M. and Breedveld P.C. (1991). *Qualitative Reasoning about Physical Systems: an Artificial Intelligence Perspective*, J. Franklin Inst., Vol. 328, No.: 5/6, pp. 1047-1065. [This paper demonstrates the natural link between a port-based approach and qualitative reasoning in artificial intelligence]

Vlerken J.J.L.M. van, Bouwstra S., Blom F.R., Fluitman J.H.J. and Breedveld P.C., (1992). *Finite-Mode Bond-Graph Model of a Resonant Silicon-Beam Force Sensor*, Int. J. of Modeling & Simulation, Vol. 12, No. 2. [This paper discussed a particular multidomain application that including a modal approach]

Vries T.J.A. de, Breedveld P.C., Meindertsma P. (1993). *Polymorphic Modeling of Engineering Systems*, Proc. 1993 Western Simulation Multiconference on Bond Graph Modeling (ICBGM '93), SCS Simulation Series, Vol. 25, nr.2, J.J. Granda & F.E. Cellier, eds., La Jolla, Cal., Jan. 17-20, ISBN: 1-56555-019-6, pp. 17-22.[This paper makes the concept of polymorphic modeling, which is implicitly present in a port-based approach, explicit for the purpose of designing tools for computer assisted modeling]

Biographical Sketch

Peter Breedveld currently is an associate professor with tenure at the University of Twente, Netherlands, where he received a B.Sc. in 1976, a M.Sc. in 1979 and a Ph.D. in 1984. He has been a visiting professor at the University of Texas at Austin in 1985 and at the Massachusetts Institute of Technology in 1992-1993, 1995, teaching integrated physical system modeling and dynamic systems and control. From June 1992 until February 1993 he was invited to lecture as visiting professor at the Massachusetts Institute of Technology and has remained an MIT affiliate since then, co-teaching in the MIT Summer Professional Program. He is or has

been a consultant to several companies, including Unilever Research in Vlaardingen, Netherlands.

In 1990 he received a Ford Research grant (the first in continental Europe outside of Germany) for his work in the area of physical system modeling and the design of computer aids for this purpose. He is an associate editor of the 'Journal of the Franklin Institute', SCS 'Simulation' and 'Mathematical Modeling of Systems'. He organized several (groups of) sessions at various scientific congresses on Physical Systems Modeling. He frequently is a member of the International Program Committees of scientific conferences related to his field of expertise. He has been or is organizing and teaching intensive courses on integrated physical systems modeling in various countries. He authored or co-authored well over 140 scientific papers or chapters and 5 books. In August 1991 he was the guest editor of a special double issue of the Journal of the Franklin Institute on 'Current Topics in Bond Graph Related Research'. Apart from presentations of conference papers he delivered over 75 speeches on his work, many of them invited. He was involved in supervising over 20 Ph.D. theses, many of them external. He was 9 times a co-advisor for a PhD thesis, 7 times 'rapporteur' in PhD/Habilitation committees in France (in Parijs, Lyon and Lille) and he was 9 times member of a PhD committee, of which 5 external from UT. From September 1, 1992, until November 1995 he was the scientific coordinator of the European ESPRIT project OLMECO (Open Library of Models of Mechatronic Components, EC 60521, project size: US $6 Million, 45 man years), involving several European companies and research laboratories, with Peugeot S.A. as project coordinator.He has been an author for the Dutch Open University. He currently participates in the Fifth Framework European Community project 'Geoplex' (IST-2001-34166), on 'Geometric Network Modeling and Control of Complex Physical Systems'.

In 1983, together with his former thesis supervisor, Prof. Ir. J.J. van Dixhoorn, he initiated and since then supervised, the development of the Computer-Aided Modeling, Analysis and Simulation (CAMAS) package, that now has become a successful commercial package under the name 20-SIM, marketed by Control Lab Products. Many companies like Philips, Ford, Toyota, Peugeot/Citroen S.A, Unilever, to mention the larger ones, and many academic institutions on all continents use this software.

In January 1993 he was the invited plenary speaker during the '93 International Conference on Bond Graph Modeling and Simulation, organized by the Society for Computer Simulation.

In October 2000 he was invited to give a series of lectures on bond graph modeling at Aisan Industry, Nagoya, Japan, a Toyota subsidiary.

In February 2003 he was an invited plenary speaker at the fourth MathMod conference in Vienna.

Among his scientific interests are: integrated modeling and design of physical system dynamics; mechatronic design; dynamics of spatial mechanisms; generalized thermodynamics; graphical model representations (bond graphs); computer-aided modeling, simulation and design; control; numerical methods; applied fluid mechanics; applied electromagnetism; generalized networks; qualitative physics; knowledge-based systems; sensors and actuators, currently in particular surface acoustic wave motors (patent pending).