MODELING AND SIMULATION OF DYNAMIC SYSTEMS USING BOND GRAPHS

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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 *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 of Dynamic Systems*)

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

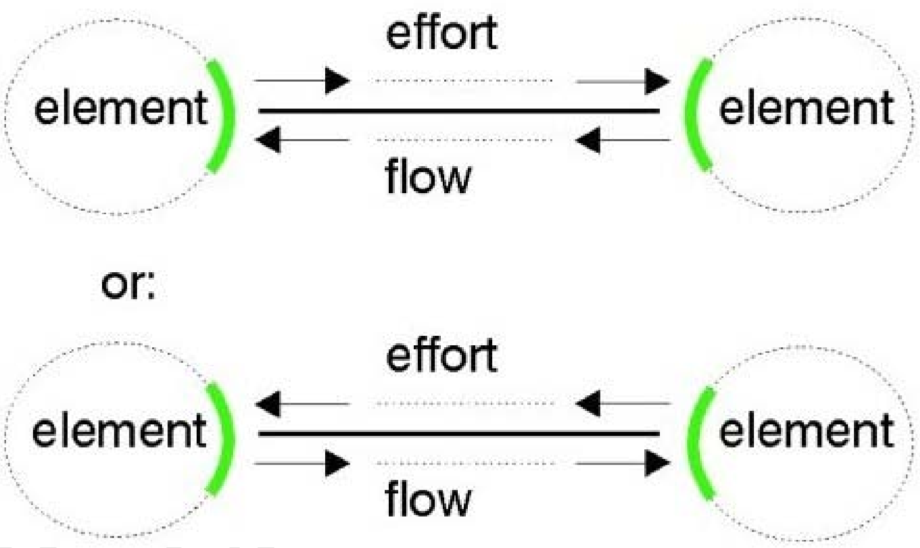

Figure 1: Bilateral signal flows between ports

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 22).

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.

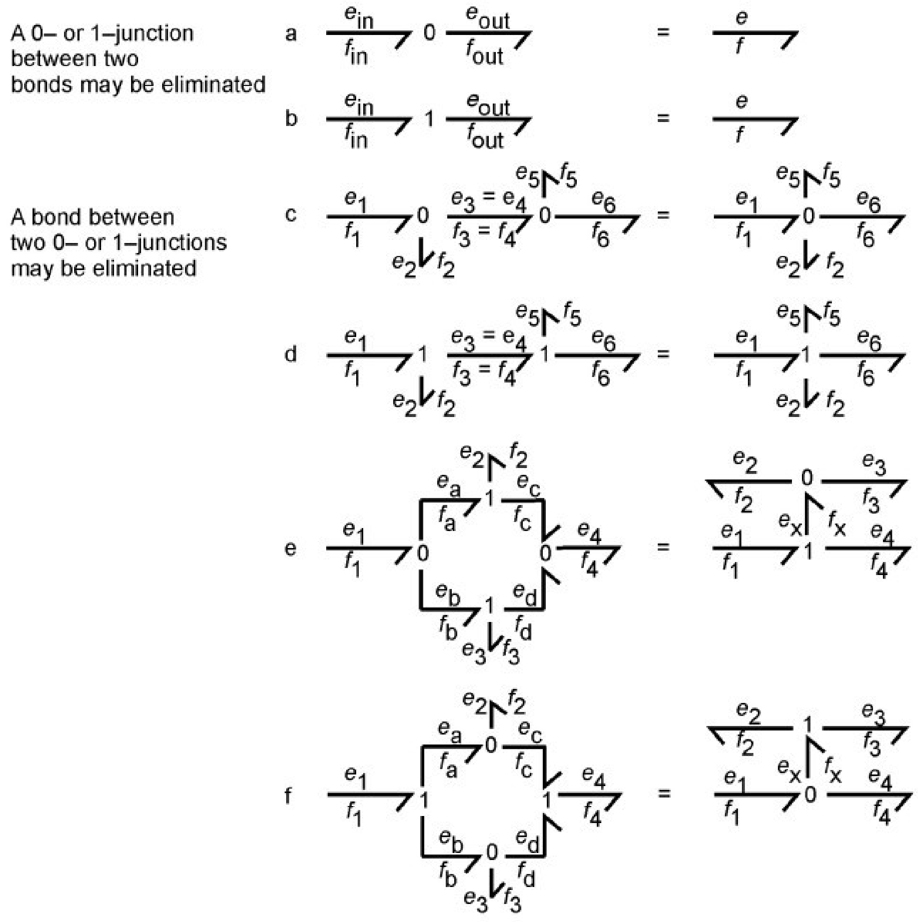

Table 2: Equivalence rules for simple junction structures

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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).