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Igor Milanović[1)]
Dragan Milosavljević[2)]
Miladin Stefanović[2)]
Zora Arsovski[1)]
Dragana Rejman Petrović[1)]

1) Faculty of Economics, University of Kragujevac, Serbia {djidji, zora, rejman}@kg.ac.rs
2) Faculty of Engineering, University of Kragujevac, Serbia {dmilos, miladin}@kg.ac.rs

SUPPLY CHAIN INFORMATION FLOW MODELING WITH BOND GRAPHS

Abstract: *Bond graphs are graphical descriptions of the dynamic behavior of physical systems independent of the domain. This means that systems with different domains (electrical, mechanical, hydraulic, acoustic, thermodynamic, and chemical, etc.) can be described on the same way. The basic premise of all modeled systems is that their appropriate bond graphs are based on the maintenance and exchange of energy.*
To describe the dynamic characteristics of the information flow in the supply chain, methodology for modeling using bond graphs can be used. Bond graphs help to significantly simplify the analysis of some phenomena that arise in the supply chain with respect to the numerous restrictions and requirements.
Keywords: *supply chain, bond graphs, modeling, information flow*

1. INTRODUCTION

As it can be seen from the perspective of flow of materials, products or semi-finished products, supply chains can be presented as a network of transformation and accumulation (storage) elements (objects) that are associated with channels passing materials, semi-finished and finished products, similar as in the case of a network of roads where passing vehicles. In addition to product flow, exist also information flow which is not less important for the analysis.

An efficient system of management with knowledge of mechanisms and principles of functioning of variables that describe this phenomenon should be used for further analysis based on models. Bond graphs could be used for that purpose.

2. BOND GRAPHS

Bond graph modeling is a powerful tool for modeling engineering systems and is a form of *object-oriented* physical systems modeling [1].The concept of energy as the starting, common point in studying the behavior of the system is not new. With that kind of approach to the problem were first faced Hamilton and Lagrange, and later Firestone and his contemporaries. In recent years, it is important to mention H. M. Paynter, professor from Cambridge, who came to the idea in 1955 of a graphical presentation of the system with bond graphs, also known as power connection graphs or power flow through system graphics. His first work in this area, Analysis and Design of Engineering Systems, was published in 1961 and this year is the beginning of theory of bond graphs [4].

The idea was further developed by Wellstead [5], Karnopp and Rosenberg in their textbooks [6, 7], such that it could be used in practice [8, 9]. By means of the formulation by Breedveld [10] of a framework based on thermodynamics, bond graph model description evolved to a systems theory.

This method is a graphical method for obtaining a mathematical model of an arbitrary physical system, i.e. its application leads to the equations of motion (states), and it is possible to calculate the transfer function of the system. The task of the method is to specify energy interactions in the system over the energy connections between the elements, so called bonds. Therefore, the elements of physical systems are considered as energy converters.

2.1 Model types

The observed systems can be presented with different types of models: graphical (drawing scale), network, bond graphs, block diagrams and mathematical (Figure 1).

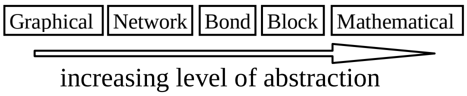

Figure 1. Model types

Network models are used for modeling of electrical and hydraulic systems, and the block diagrams are used in the field of automatic control and regulation. Bond graph is combination of the two previous models with their best features. The main difference between them is in the labeling. While the elements of network models are graphic diagrams, bond graphs are using letters. Good characteristics of the bond graph shows elements connect through junctions (node fields) and causality of power relationships. The first feature is taken from the network model and second from block diagram. Also, good quality of bond graph is that systems with different types of energy are considered as a whole, i.e. without separation into smaller subsystems.

2.2 Variables

The energy related to elements of the system can be presented by two system variables whose product is the current power that system can transmit.

Flow (f) variable presents flux, i.e. amount of energy went through the element per unit of time. The flow variables describing something moving ***through*** the element: the current through the resistor, the fluid through the pipe, etc.

Effort (e) variable presents a change of energy flow. The effort variables measures the ***difference in states*** at the entrance and exit of element, such as the voltage drop across the resistor, the pressure drop between the ends of a pipe, the difference in speeds at the ends of coil, etc.

This means that the flow, as through variable, is related to a ***single point***, while the effort, as across variable, present the difference between the values measured at ***two different points***, at the beginning and end of an element of the system.

These two together make up a mechanism for energy transfer (Figure 2) and have a correspondence in practically all physical fields.

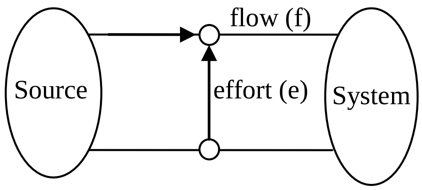

Figure 2. Mechanism for energy transfer

Two other variables, the moment (p) and the displacement (q), called stored energy variables, are also defined by integrating the power variables (e and f) according to time. Those four variables are state variables where their knowledge allows knowing the state of the whole considered system. They specify the time history of energy flow within a system.

2.3 Model conversion

Basic assumptions that are valid for variables during conversion from physical to mathematical model are:

1) ***Physical variables definition.***

When defining a system it is necessary to select accurately the physical variables (velocity, strain, pressure, flow, etc.) that describe the current state of the system, and by which the behavior of the system could be uniquely defined.

2) ***Equilibrium and compatibility relationships.*** These two types of relations together are called the ***system relationships***.

Equilibrium relations are always related to flow variables. These include nodal relations, relations of continuity, flow, relationships concerning a single point of system. These relationships reflect the balance of speed, continuity of flow, maintenance of energy and are valid for the entire system and for its subsystems.

Compatibility relations are always related to the effort variables. These are, for example, contour relationships, i.e. relations that are related to a closed path in the system. They describe how changes in individual elements of the system depend on their connection with other elements.

3) ***Physical relationships.*** Represent the relationships between flow and effort variables. In other words, each element individually meets the relevant laws of nature, such as for example mechanics relation between force and displacement, the electrical between current intensity and voltage, electro-mechanical between force and the magnetic field intensity, thermodynamical relationship between temperature and heat flow, etc. All these relations together are called ***constitutive relationships***, because they are specific to certain element, i.e. constituent of the system.

To obtain the equations of motion (states) it is necessary to combine system and constitutive relations. Before that, system boundaries should be defined, as well as linearization of constitutive relationships, to make problem resolving easier.

2.4 Standard elements

The standard bond graph elements that will be defined below are two basic active elements, three basic one-port passive elements, two basic two-port elements and two basic junctions (Table 1). Each of these elements, along with a link (bond), is more than mathematical relation. Together they define the input-output characteristics and direction of energy flow.

2.4.1 Active elements

There are two main sources of energy for any system – source of effort and source of flow. For the source of effort, the effort is independent on flow at the exit of the element, and for the source of flow, the flow is independent on flow at the exit of the element.

2.4.2 One-port elements

There are three different types of one port elements, which in electrical systems are: C – capacitance, and I – inductance, as electrical flow storage (accumulators), and R – resistance as energy consumer (dissipator).

2.4.3 Two-port elements

Two-port elements can be divided into: transformers, as energy converters, which make a direct connection of the flow and effort variables (e-e and f-f relationships) and gyrators (cross-transformers), performing cross-linking of effort and flow variables (e-f and f-e relationships). In contrast to one-port elements, they have two energy ports, input and output, which means that they perform power (energy) conversion.

2.4.4 Junctions

Connecting the various elements of the system can be serial or parallel. Characteristics of sequential or serial connection are that the total effort is equal to the sum of efforts, and the flow through each element is the same. Characteristics of parallel connection are that the total flow is equal to the sum of the flow, and the effort of each element is the same. Serial and parallel connection of elements in the bond graph can be presented by effort and flow junctions respectively.

Flow junctions (P or 0) are paralel junctions. In them efforts are equal, while the amount of flows we put into junction equals the sum of the flows coming out of the junction.

Effort junctions (S or 1) are serial junctions. In them flows are equal, while the amount of effort we put into junction equals the sum of the efforts coming out of the junction.

It can be said that junction structures represent two Kirchoff's law.

Table 1 – Elements of bond graphs [2]

Element	Symbol	Constitutive relations
R-element (Resistor)	e, f → R	$f = e/R$
C-element (Capacitor)	e, f → C	$e = \frac{1}{C}\int f\,dt$
I-element (Inductor)	e, f → I	$f = \frac{1}{I}\int e\,dt$
TF (Transformer)	e_1, f_1 → TF (m) → e_2, f_2	$e_2 = m\,e_1$; $f_1 = m\,f_2$
GY (Gyrator)	e_1, f_1 → GY (k) → e_2, f_2	$e_1 = k\,f_2$; $e_2 = k\,f_1$
0–junction	e_1, f_1; 0; e_3, f_3; e_2, f_2	$e_1 = e_3$; $e_2 = e_3$; $f_3 = f_1 - f_2$
1–junction	e_1, f_1; 1; e_3, f_3; e_2, f_2	$f_1 = f_2$; $f_3 = f_2$; $e_2 = e_1 - e_3$
Flow source	Sf : F(t) e, f	$f = F(t)$; e = free
Modulated flow source	u → MSf e, f	$f = u$; e = free
Effort source	Se : F(t) e, f	$e = F(t)$; f = free
Modulated effort source	u → MSe e, f	$e = u$; f = free

2.5 Causality

The input-output causality is a very useful tool in modeling systems, because it allows later addition of input-output functions to effort and flow variables with the help of causal hyphens. This is done by using the causal convention shown in Figure 3. The direction of semi-arrow (power transfer) is not important for this convention, which means that it can be to or from the element.

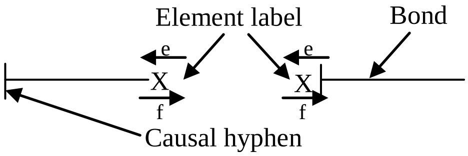

Figure 3. *Causal convention*

Characteristics of each bond are that above it is written label of effort variable (e), and under is flow variable (f). In Figure 3 with X is marked an element, and the arrows next to variables indicate which variable is taken as input and which as output from the element. Causal hyphen is placed normal to one end of the bond.

Causal conventions can be defined as follows: If element and hyphen are located at the same side of bond, then input variable to element is effort, and output variable is flow. Otherwise, if element and hyphen are from different sides of bond, then input variable to element is flow, and output variable effort.

It is important to make distinction between labeling of causality and power flow: semi-arrow of power flow shows adopted positive direction of power transmission, and causal arrow indicates which of variables is adopted for input and which for output from the element.

2.5.1 Active elements causality

Source of effort (Se) gives effort at the output, and source of flow (Sf) gives flow at the output. For these types of elements these are the only possibilities for distribution of output values.

2.5.2 One-port elements causality

For all three elements both causalities are possible.

2.5.3 Two-port elements causality

For transformers causality for output bond is the same as causality of input bond, while the reverse is in the case of gyrator, where causality of input and output bond are different.

2.5.4 Junctions causality

For these elements determination of causality is more complex, i.e. there are certain rules.

For effort junction causality (output flow causality) all bonds have the output flow in relation to the junction, but one that has the input flow. This simplified means that around effort junction on every bond hyphens should be drawn next to junction, except one where bond causal hyphen is on the other side of junction.

For flow junction causality (output effort causality) all bonds have the output effort in relation to the junction, but one that has the input effort. This simplified means that around flow junction on every bond hyphens should be drawn on the other side of junction, except one where bond causal hyphen is next to the junction.

2.6 Assigning causality to bond graph

After drawing a bond graph it is necessary to assign causality too. In assigning causality to bonds following tasks should be accomplished:

1) uniquely determined causalities for sources of energy are assigned first,

2) as long as possible, assigning of preferred (integral) causalities to accumulators is done, taking into account the causalities of two-ports elements and junctions that are higher priority,

3) at the end, assigning of causalities to dissipators should be done. If remains a dissipator which causality is not determined, an arbitrary causality will be assign to it and, thus, complete casuality of the graph.

Based on above mentioned it can be established following list of priorities in determining causalities:

1) sources of energy,
2) junctions,
3) two-port elements,
4) accumulators, and
5) dissipators.

3. ANALOGIES

The equations of motion and behavior of different physical systems indicate that there are great similarities between them. This means that if one requires more information about bulky mechanical systems, he can make the appropriate analogue electrical system on the basis of their behavior, and can make conclusions about the behavior of mechanical systems. In addition, the results are very accurate and this method of testing is quite cheaper and simpler.

Procedures for deriving equations of motion for different physical systems are almost the same, the equations have the same form and almost every physical variable in a system has a corresponding analogue in other system (Table 2).

Analogies provide many benefits. If one discovers some new findings, in the study of a system, then it may be applied on its analogues. Analogies can be harmful when they apply for physical laws that are impossible. On the other hand, the analogy is very useful in the detection of system behavior with which we meet for the first time through its analogues whose behavior is clearly due to better knowledge of such systems.

In this study, we used the analogies, primarily with the physical flow of products through the supply chain.

Table 2 – Classification of analogies between different physical systems

Classification		Electrical	Mechanical	Thermal	Fluid
Variable	**Flow**	i	v	q	Q
	Effort	u	F	T	p
Relationship	**Equilibrium**	$\sum i=0$	$\sum v=0$	$C\times dT/dt=q_{net}$	$dV/dt=Q_u-Q_i$
	Compatibility	$\sum u=0$	$\sum F=0$	$\sum T=0$	$\sum p=0$
	Physical	$i=1/L\times\int udt$	$v=1/m\times\int Fdt$	?	$i=1/L_f\times\int pdt$
		$i=C\times u'$	$v=1/c\times F'$	$q_{net}=C_T\times T'$	$Q=C_f\times p'$
		$i=u/R$	$i=F/b$	$q=1/R_T\times(T_1-T_2)$	$Q=1/R_f\times(p_1-p_2)$
Source	**Flow**	i(t)	v(t)	q(t)	Q(t)
	Effort	u(t)	F(t)	T(t)	p(t)

4. CASE STUDY

The supply chain is always composed of several parties (suppliers, manufacturers, assemblers, distributors, retailers and customers) situated in distant geographical areas (Figure 4). The dependence between these parties is a share in the delivery of products (product flow), through the transport logistics, in processing order (information flows) and financial transactions (financial flow) [2].

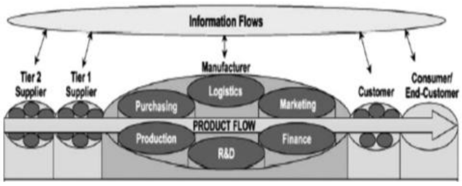

Figure 4. *Supply Chain Model [10]*

Here, attention is payed especially on information flow aspect of supply chain.

If one observe small and medium enterprises in the existing supply network, the SC partners export data that are of common interest in e-hub (information hub or junction), so that the current data is always available to all members of the network [12].

In order to build an integrated B2B supply chain network, there must be an exchange and market place that understand all document structures to facilitate business data interchange services. One important approach to B2B supply chain integration is e-hubs that instantly process and forward all relevant information to all appropriate partners along the supply chain, so that the entire supply chain can work as a whole (Figure 5).

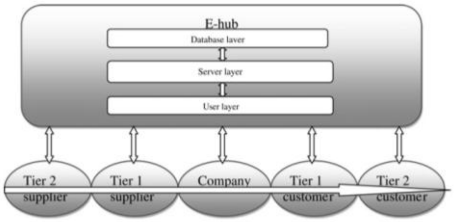

Figure 5. *E-hub architecture [10]*

Most companies are not able to respond to events in the environment without the help of its partners. The existence of information barriers between partners causes delays in delivery and time consumption for resolving misunderstandings and errors in communication.

The rise of the Internet has made it possible to virtually integrate various channel members and functions of a supply chain. All participants can transfer the information in real time with least transaction cost and global reach by using the Internet as the main medium.

4.1 Comparision of product and information flow elements

Information flow is result of operations of storage, displacement or transformation made on information. The revealing of these operations is possible through the existence of diferent elements:

- Storage elements are used for keeping the information pending transformation and output,

- Displacement elements are information networks and Internet,
- Transformation elements are queries or filters that transform information from one to another form preferable for the end user.

To present complet comparision with physical (product) flow elements (Table 3), two more elements are introduced – one for connection to input elements, and another one for connection to output elements. In information flow structure those two are requests for information or information for upload and processed information (response to requests).

***Table 3** – Comparision of product and informaton flow elements in SC [2]*

Objects	**Product flow**	**Information flow**
Manipulated object	Product	Information
Storage element	Stock	Database, table
Displacement element	Transfer way	Internet, network
	Junction	Junction
Transformation element	Machine	Query, filter
Connecting to input system	Flow source	Request for information or for upload
Connecting to output system	Well	Response to a request

4.2 Descriptive variables associated with information flow

Description of the information flow evolution within a supply chain requires obtaining different types of information.

Visibility is a very important feature of flexible supply chains. Consider the life cycle of an order created on the Internet by customer. In a perfect adaptive network, information about the order should be available to suppliers along the supply chain immediately. They can check the availability of the required components in their inventories and simultaneously respond to the request. All organizational units in the enterprise, or external partners who participate in the supply chain, may be involved in order realization and can tracking it through all stages of the supply chain, all through delivery the requested products to the buyer eventually. The possibility of tracing the status of orders is the core of visibility. The challenge that arises, regarding the visibility, is that the majority of companies still keep their data in separate systems, and the fact that external suppliers are generally not integrated into the enterprise information system.

In order to propose metrics for information flow, we use the analogy with adequate flow variable in physical (product) flow – average number of products per unit of time, and named flow variable as **average number of requests per time unit**. C-element placed on 0 junction corresponds to a communication lines and capacity value C_{max} corresponds to limited capacity of the database. The displacement variable which is defined by integrating flow variable over time represents the number of requests.

Another important characteristic of modern supply chains is the **speed of response**, i.e. the speed with which the database is able to respond to a request. In information flow analysis this is effort variable. For example, how quickly partner can respond to an order in terms of dissemination of information through the supply chain.

Ordering time is another important characteristic, since there could be problems if orders for same product come from different places simultaneously. One which was timely placed, before the others, should be preceded immediately to check out. Other orders can be realized if there are enough goods in stock.

Manufacturing time is not relevant for information flow but for product flow.

In comparision to parameters characterizing the diferent elements handling the product flow, the parameters characterizing the diferent elements handling the information flow throughout the supply chain are given in Table 4.

Table 4 – *Comparision of product and informaton flow parameters in SC [2]*

SC element	Parameter
Stock	Physical capacity C_{max}, expressed in number of products
Database	Database capacity C_{max}, expressed in number of requests
Machine	- Number of products can be processed simultaneously. - Treatment frequency of products, X_{max}
Query, Filter	- Number of information can be processed simultaneously. - Maximal speed of response, X_{max}
Flow source	Input flow
Request for information	Input information
Well	Unlimited physical capacity
Response to a request	Output information

4.3 Behavioral laws asociated with information flow

A physical flow, whatever its nature, is subject to laws governing its key variables: flow, density and speed. In case of information flow such laws could be derived from analogies with product flow.

No recognized theory of information (i.e., the statistical theory of Shannon et al, and the algorithmic theory of Kolmogorov, Chaitin, and Solomonoff) has a law of conservation of information. William Dembski and Werner Gitt have each invented their own nonstandard information theories, but neither of these theories is used in science or engineering, and their claims are not supported by the vast body of research into information theory [13].

By analogy with product flow, the flow is supposed to be always in equilibrium and evolves from a steady state to another (Table 2). It is about rule that each request for information should have adequate response.

Maximum database load per unit of time must not exceed the theoretical value given by C_{max}, which means that the sum of the number of requests and files for upload to the database, along with the number of processed information ready to be sent to SC partners, shall not be higher than C_{max}.

4.4 Modeling of the information flow transfer within a supply chain

The characteristic parameters of the support, on which are stored, transported and modified information through the supply chain, are now expressed. The variables of the information flow are previuosly described and parameters are designated. These parameters, laws and variables are considered in analogy with the product flow. A network model of information flow in supply chain is illustrated in figure 6.

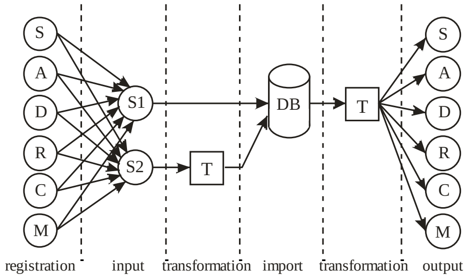

Figure 6. *Physical (network) model of information flow in supply chain*

Following simbols were used on figure 6 for modeling of information flow through supply chain: S – suppliers, A – assemblers, D – distributors, R – retailers, C – customers, M – manufacturers, S1 – request for information, S2 – information for upload, T – queries or filters, DB – database (information junction, e-hub).

It is noticeable that the entire communication between the partners, in the supply chain, actually operates through an information hub and, in contrast to the horizontal movement of products, has the character of the vertical connectivity. In Figure 6 one can see the entire supply chain on the left and right area of the physical model. In bond graphs modeling it will not be noticeable since here are consider the impact of information only. In relation to entry into modeling of bond graphs are two kinds of requirements that can generate any partner of the supply chain, which are a request for information and files for upload.

Request for information could be about: actual offer, actual state of an order, stock, actual position of tranportation vehicle, delivery time, etc. The request should be submited on web portal after partner registration and an answer will be generated from the database after querying or filtering.

To have actual state of data in database, each partner should timely upload information about: stocks, prices, availability, manufacturing time, delivery time, transportation, etc. Since many partners could have different file formats for upload, transformation by querying should be applied before inserting into database.

At the end, bond graph model is presented on figure 7. Graph has been drawn with 20-sim 4.2 Controllab Products B.V. 2011 software. This software can support realization of different kinds of model together with simulation. The software can automatically determine the causality of elements and correct errors that arise from bad elements connections.

Meaning of symbols are given in addition. MSf (S1 and S2) are sources of two different flows – request for information and files for upload, where f_{s1} is average number of requests per unit of time and f_{s2} is average number of files for upload per unit of time. MTF (TF1 and TF2) are modulated transformations for files upload and requests for information. R_{1min} and R_{2min} are minimum of time necessary for upload and response to a request. C_{max} is maximum database load.

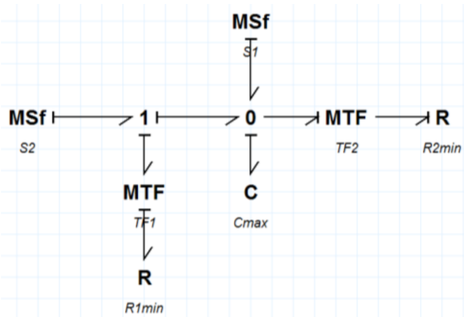

Figure 7. *Bond graph model of information flow in supply chain*

5. CONCLUSION

In this paper, research about implementation of bond graph modeling for information flow through supply chain has been performed. Previously realized research made for physical flow transfer [2] was the basis for comparision and further analisys.

After performed comparision analisys, following conclusions has been made:

- storage, displacement and transformation elements exists in both cases (Table 3),
- descriptive variables are different, but analogies between parameters exists (Table 4),
- lack of behavioral laws asociated with information flow, and
- derived bond graph model can be used for simulation with adequate software.

REFERENCES:

[1] Broenink, J. (1999). Introduction to Physical Systems Modelling with Bond Graphs, *SiE Whitebook on Simulation methodologies*, Enschede, Netherlands: Univ. Twente Press

[2] Benmansour, S., Bendriss, S., Banabdelhafid, A. (2011). Bond Graph Model of the Physical Flow Transfer within a Supply Chain, *Fourth International Conference on Logistics, May 31 – June 3, 2011, Hammamet, Tunisia*, ISBN: 978-1-4577-0322-5, 349-356, doi: 10.1109/LOGISTIQUA.2011.5939314

[3] Smata, N., Tolba, C., Boudebous, D., Boukachour, J. (2010). From Car Transport to Supply Chain: Modelisation and Performance Evaluation, *EFEEA'10 International Symposium on Environment Friendly Energies in Electrical Applications, 2-4 November 2010, Ghardaia, Algeria*, 1-7

[4] Paynter, H.M. (1961). *Analysis and design of engineering systems*, MIT Press, Cambridge

[5] Wellstead, P.E. (1979). *Introduction to Physical System Modelling*, Academic Press, London

[6] Karnopp, D.C., Rosenberg, R.C. (1968). Analysis and Simulation of Multiport Systems – The bond graph approach to physical system dynamics, MIT Press, Cambridge

[7] Karnopp, D.C., Margolis, D.L., Rosenberg, R.C. (1990). System dynamics, a unified approach, (2nd edition), J Wiley, New York, NY, ISBN 0 471 45940 2

[8] Thoma, J.U. (1975). Introduction to bond graphs and their applications, Pergamon Press, Oxford

[9] Dixhoorn, J.J. van, (1982). Bond graphs and the challenge of a unified modelling theory of physical systems In Cellier F.E. (Eds.), *Progress in modelling and simulation*, (pp. 207-245). New York: Academic Press

[10] Breedveld, P.C. (1985). Multibond–graph elements in physical systems theory, *Journal of the Franklin Institute, vol 319, no 1/2*, 1-36

[11] Xiaofeng, Z., Hui, Z., Jianrong, H. (2010). B2B e-hubs and information integration in supply chain operations, *Management Research Review, Vol. 33, Iss: 10*, 961 – 979

[12] Milanović, I., Stefanović, M., Arsovski, Z., Rejman Petrović, D., Ranković, V., Kalinić, Z. (2011). Supply Chain Information Integration Methods from Quality Aspect, *5th International Quality Conference, Center for Quality, Faculty of Engineering, University of Kragujevac, Serbia, Proceedings, COBISS.SR-ID 183653388, ISBN 978-86-86663-68-9, May 20, 2011*, 439-448, http://www.cqm.rs/2011/cd/5iqc/pdf/055.pdf

[13] Elsberry, W., and Shallit, J. (2003). Information theory, evolutionary computation, and Dembski's "complex specified information", http://www.talkreason.org/articles/eandsdembski.pdf

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