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Tolujew J.

doctor of technical sciences, professor, Fraunhofer Institute
for Factory Operation and Automation, Germany, Magdeburg
Transport and Telecommunication Institute, Latvia, Riga,
e-mail: juri.tolujew@iff.fraunhofer.de

GRAPHIC METHOD FOR MODELING MATERIAL FLOWS IN SUPPLY CHAINS

Estimation and optimization of material flows is one of the pivotal tasks in supply chain management. In order to solve it, various analytical and simulation models are utilized, and for each specific type of model, both advantages and disadvantages are known. For analytical models, the compactness of the outlook and universality of application are characteristic, however they usually reflect many real processes in real supply chains very approximately. Additionally, almost all analytical models are static, namely they do not display the dynamics of processes in time. In simulation models, on contrary, real processes may be displayed as detailed as it is desired. However, the development and use of such models is combination with large expenses in time and financial resources. This paper reports on a class of dynamic models for processes in supply chains with material flows and stock levels are displayed as so-called Quantity-Time Diagrams (QTD). Such diagrams are used not only for graphical display of actual or planned processes, but also for the numerical calculation of new processes considering data on related processes, the characteristics of which are assumed to be specified. QTD-based models reflect the dynamics of processes in supply chains, but their development and use are distinguished by significantly lower costs in comparison with those that are typical to work with simulation models.

Key words: Supply Chain Modeling, Material Flow, Quantity-Time Diagrams.

Толуев Ю.

т.ғ.д., профессор, Фраунгофер өндірісті ұйымдастыру және
автоматтандыру институты, Германия, Магдебург қ.
Көлік және байланыс институты, Латвия, Рига қ., e-mail: juri.tolujew@iff.fraunhofer.de

Жабдықтау тізбектеріндегі материалдық ағындарды модельдеудің графикалық әдісі

Материалдық ағындарды бағалау және оңтайландыру жабдықтау тізбегін басқарудың негізгі міндеттерінің бірі болып табылады. Оны шешу үшін аналитикалық және имитациялық модельдердің әртүрлі типтері пайдаланылады және әрбір модельдің артықшылықтары мен кемшіліктері белгілі. Аналитикалық модельдерге презентация түрінің ықшамдылығы және қолданылу әмбебаптығы тән, бірақ олар, әдетте, нақты жабдықтау тізбектеріндегі көптеген процестерді жобалап көрсетеді. Сонымен қатар, барлық аналитикалық модельдер статикалық болып табылады, яғни олар уақыт кеңістігін бағалай алмайды. Имитациялық модельдерде нақты процестерді егжей-тегжейлі көрсетуге болады, бірақ мұндай үлгілерді әзірлеу және пайдалану уақыт пен қаржы ресурстарының үлкен шығындарын қажет етеді. Мақалада жабдықтау тізбектеріндегі динамикалық модельдердің жаңа классы сипатталған, онда материал ағындары мен қорлар «Quantity-Time Diagrams» (QTD) түрінде көрсетіледі. Мұндай диаграммаларды тек қолданыстағы немесе жоспарланған процестерді графикалық көрсету үшін ғана емес, сонымен қатар сипаттамалары белгілі көршілес процестер туралы деректерге негізделген жаңа процестерді сандық есептеу үшін де пайдалануға болады. QTD негізіндегі модельдер жабдықтау тізбектеріндегі процестердің серпінін көрсетеді, бірақ олардың дамуы мен қолданылуы имитациялық модельдермен жұмыс істеуге тән ерекшеліктермен салыстырғанда айтарлықтай төмен шығындарды қажет етеді.

Түйін сөздер: жабдықтау тізбегін модельдеу, материалдық ағын, үдеріс диаграммасы.

Толуев Ю.
д.т.н., профессор, Фраунгоферовский институт организации и
автоматизации производства, Германия, Гагдебург
Институт транспорта и связи, Латвия, г. Рига, e-mail: juri.tolujew@iff.fraunhofer.de

Графический метод моделирования материальных потоков в цепях поставок

Оценка и оптимизация материальных потоков является одной из основных задач управления цепями поставок. Для её решения применяются различные типы аналитических и имитационных моделей, причём для каждого типа моделей известны как его достоинства, так и недостатки. Для аналитических моделей характерными являются компактность формы представления и универсальность применения, но они, как правило, лишь очень приблизительно отображают многие процессы в реальных цепях поставок. Кроме того, почти все аналитические модели являются статическими, т.е. в них не отображается развитие процессов во времени. В имитационных моделях реальные процессы могут быть отображены как угодно детально, но разработка и использование таких моделей связаны с большими затратами времени и денежных ресурсов. В работе описывается новый класс динамических моделей процессов в сетях поставок, в которых материальные потоки и запасы в накопителях отображаются в виде так называемых Quantity-Time Diagrams (QTD). Такие диаграммы могут быть использованы не только для графического отображения существующих или планируемых процессов, но и для численного расчёта новых процессов на основании данных о смежных процессах, характеристики которых считаются заданными. Модели на базе QTD отображают динамику процессов в цепях поставок, но их разработка и применение связаны с существенно меньшими затратами по сравнению с теми, которые характерны для работы с имитационными моделями.

Ключевые слова: моделирование цепей поставок, материальный поток, диаграмма процесса.

Introduction

This paper considers general supply chains as an object of the study. Such general supply chains, in the structure of which sources (suppliers), sinks (buyers) and intermediate nodes serving as transport channels along with warehouses and transshipment points are defined. The urgent need to analyze and simulate such systems arises both in connection with the work on the design of new systems and with the modernization of current systems. For instance, as part of consulting or logistics audit. The pivotal purpose of the simulation is to obtain numerical estimates of the performance indicators in the system under consideration for such modes that have not yet been observed in reality.

Traditional methods for calculating material flows may be divided into static and dynamic. As static models, flow models in the form of transport matrices are used widely (Gudehus et al, 2016). Models of queuing theory are also considered to be static (Masek et al., 2015; Bhaskar et al., 2010). Although the models that belong to this class are applied to analyze the dynamic processing of customers, the simulation results (formulas) in the vast majority of cases refers only to the stationary mode of operation. They allow a user to calculate the performance of the system in the form of average values and do not contain any «dynamics». The optimization models that are defined and approached using mathematical programming methods are also static (Shapiro, 2001). On the other hand, simulation models based on the processing discrete events principles (discrete event simulation) (Law et al., 2000), or continuous models of system dynamics according to Forrester are dynamic by their fundamental nature (Sterman, 2000). The mesoscopic approach is a comparatively new in supply chain modeling (Hennies et al., 2014). Although today anyLogistix tool (Ivanov, 2017) is offered for simulation of arbitrarily complex supply chains, such models appear relatively seldom due to the high labor intensity required for their creation and use (Hicks, 1999; Kumar et al., 2013).

This paper describes a class of dynamic models of processes in supply chains in which material flows and stock levels are displayed as so-called Quantity-Time Diagrams (QTD). Such diagrams are applied not only for graphical display of actual or planned processes, but also for the numerical calculation of new processes based on data on related processes, the characteristics of which are considered to be specified (Tolujew, 2003).

Key properties of a discrete material flow

Continuous material flows may be observed in case of liquid goods transported via pipelines or bulk goods using conveyor belts. In the following sections, only discrete flows will be taken into account, which are defined as sequences of events, each of which stands for a certain number of cargo units, which may contain both piece and liquid or bulk cargo that appears at a certain point in the logistic chain. Figure 1 demonstrates loading units as objects of the material flow Ob.k.m, where k stands for the designation of the load type, and m represents the sequence number of the batch arriving in the flow under consideration. Each batch of the cargo is characterized by its volume. In the simplest case, this volume can be measured either by the number of pallets or other cargo holders included in the corresponding batch. There are no problems if the quantity of products, its weight or spatial volume is indicated for a batch of cargo.

Figure 2 shows an example of a discrete material flow, in which the number of pallets included in its composition is indicated for a batch of cargo. Such a flow can be observed, for example, at the warehouse entrance, when each event stands the unloading of a certain number of pallets from the arriving truck. Using a separate form of presentation of a material flow, each event is presented as the number of pallets delivered during this event. The cumulative flow form is the result of the integration of the separated flow. Being applied for each event, the total number of pallets delivered from the time the observation begins is shown. Figure 2 demonstrates six events in the warehouse input flow, which resulted in 46 unloaded pallets.

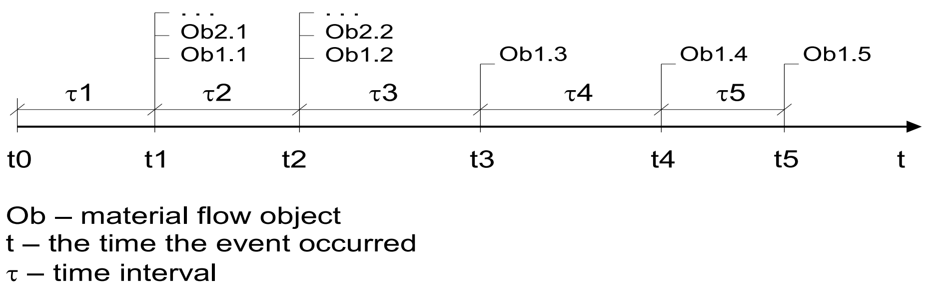


Figure 1 – Graphic model of a discrete material flow

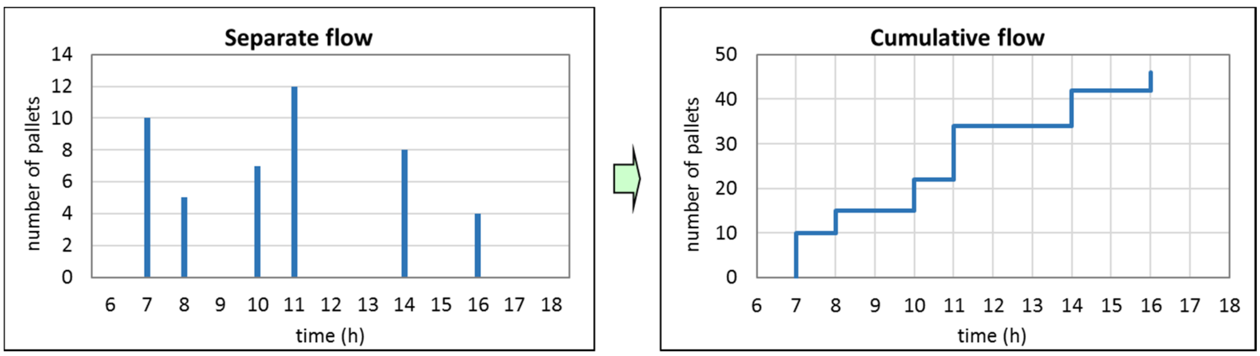


Figure 2 – Representation of the material flow in separate and cumulative forms

The separate form of flow representation is closer approximated to reality, and the cumulative form is applied as the basis to calculate the stock level (see Figure 3). Any storage place for goods or a transport channel can be treated as a storage device, which can also be considered as a warehouse, the entrance and exit of which are separated from each other by the transportation distance. Figure 3 shows six events in the input flow of the storage and three events in its output flow. For both flows, their graphs are constructed in a cumulative form. The dynamics of the stock in the storage is calculated as the difference between the input and output flows, presented in a cumulative form.

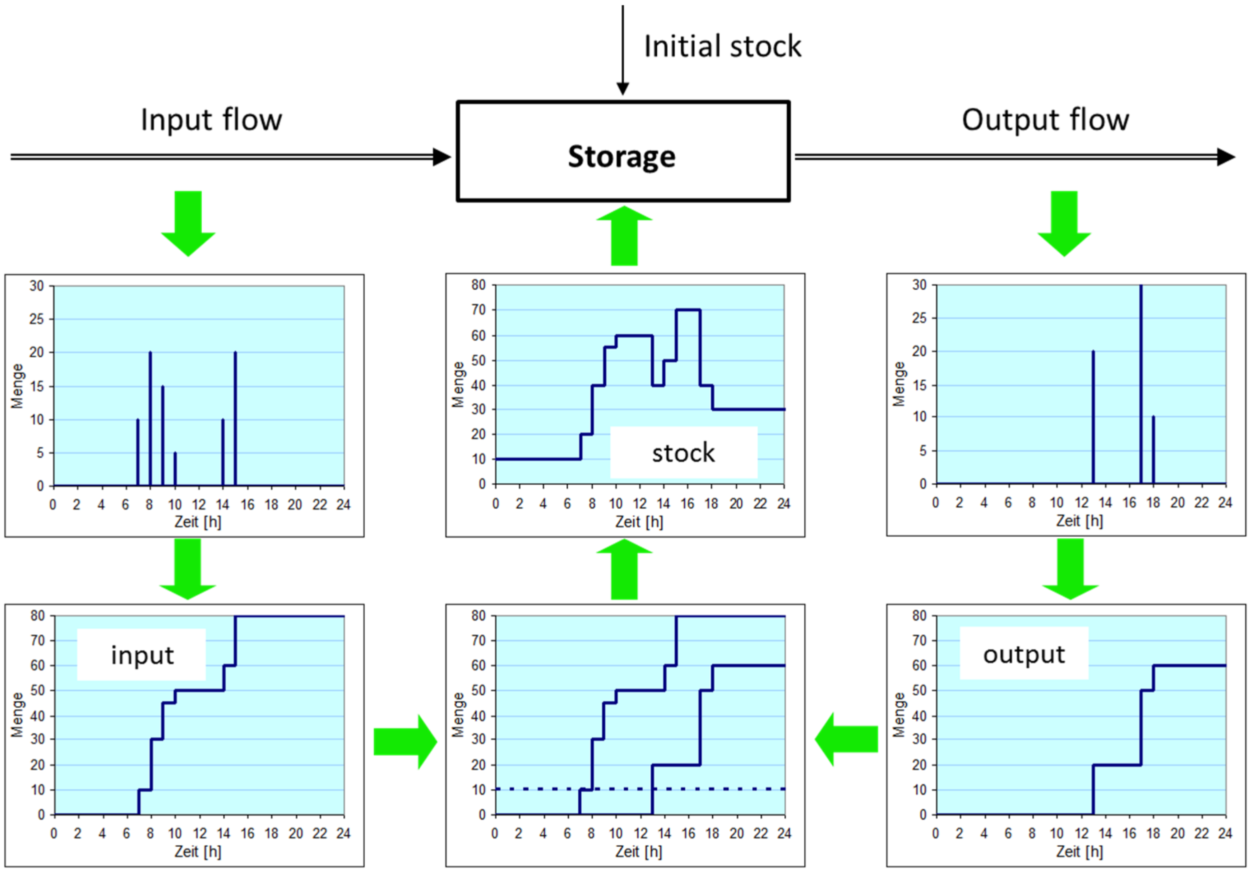


Figure 3 – The method for calculating the storage dynamics

Design and use principles of Quantity-Time Diagrams

Figure 4 demonstrates the system for processing material flows in the form of a queuing system. Let's assume that exactly 9 customers come from source 1 to the system, of which seven customers are sent to queue 2, and two customers to queue 5. Thus, the input flow T(1,2) contains seven events, and the input flow T(1,5) two events respectively. In Figure 4, both input flows are shown in cumulative form. Similarly, in the form of flows T(2,3), T(3,4), T(5,6) and T(6,4), the transitions of customers between the other nodes of the system are shown. Nodes 2 and 5 are queues, and nodes 3 and 6 are service stations. All these nodes are storages, and the dynamics of their contents are completely determined by the dynamics of the corresponding input and output flows. Figure 4 shows the situation when the processing of all 9 applications has not yet ended. A full description of the described situation looks like this:

– 7 customers entered the station 2, 5 customers exited, and 2 customers are still in the station 2;

– 2 customers entered the station 5 and exited immediately after that, thus the station 5 is empty;

– 5 customers entered the station 3 and 4 customers exited it, therefore one customer is still processed;

– 2 customers entered the station 6 and only one customer exited it, thus one customer is still processed.

Figure 5 shows the conventional transport matrix «Static material volumes». It contains all the transitions of material objects that should be fixed at the end of the simulated process. The sums of the objects in rows and columns of the matrix are also shown. For instance, the sum in row 1 shows all 9 objects that came from source 1, and the sum in column 4 shows all 9 objects that entered the sink 4. Analogously with this matrix, a second matrix is defined. This matrix contains dynamic processes i.e. streams with the appropriate number of events in its cells instead of fixed numbers. A crucial point here is the ability to show on the main diagonal of the matrix the processes observed in the stocks of the system. For example, in cell (2,2) the process in queue 2 is shown, and in cell (3,3) the process in station 3 is shown.

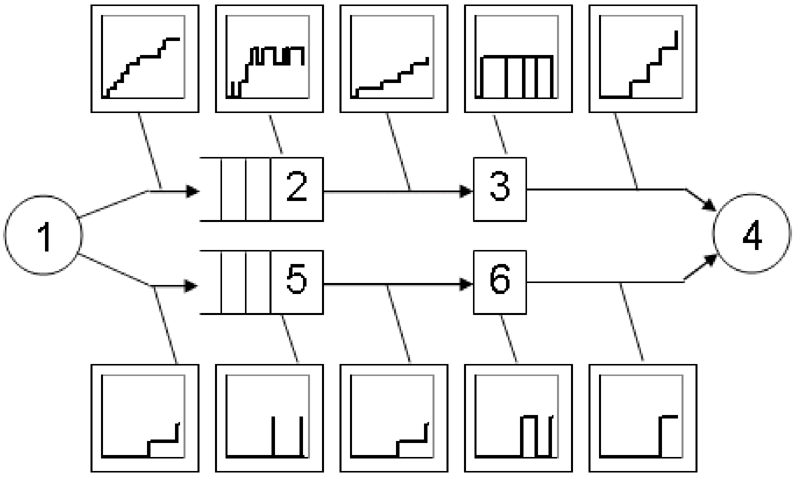


Figure 4 – Material flows in a queuing system

Static material volumes

	1	2	3	4	5	6	Σ
1		7			2		9
2			7				7
3				7			7
4							0
5						2	2
6				2			2
Σ	0	7	7	9	2	2	

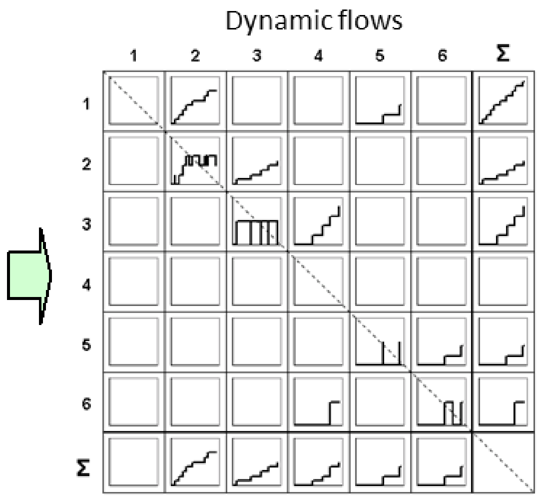
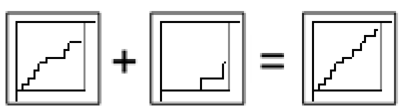


Figure 5 – Static and dynamic representation of material flows

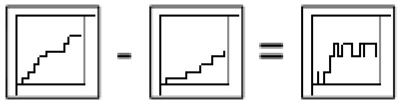
For the elements of the «Dynamic flows» matrix, the name Quantity-Time Diagram (QTD) is used. As follows from the examples discussed above, there are two types of QTDs, namely transitions T(i,j) and processes in stocks C(i). On the one hand, a QTD is the graphic form of a process representation and, on the other hand, a well-structured information array. This aspect in particular makes QTD suitable for use as operands in arithmetic, algebraic and functional transformations (Tolujew, 2003).

For instance, if the total output flow of the source 1 (Figure 4) is to be calculated, processes in edges (1,2) and (1,5) must be totaled:

Output(1) = Flow(1,2) + Flow(1,5) =



The dynamics of the current contents of node 2 can be calculated by subtracting the output flow (2,3) from the input flow (1,2):

Stock(2) = Flow(1,2) - Flow(2,3) = 

VBA and Excel were used to create a program prototype, which makes it possible to perform the following basic operations with QTD:

– *addition*: the addition of two processes; material volume or number of objects is totaled;

– *subtraction*: the subtraction of one process from another; the difference in material volume or number of objects is calculated;

– *a-multiplication*: multiplication of amplitude; material volume or number of objects is increased or decreased;

– *f-multiplication*: multiplication of frequency; number (frequency) of events is increased or decreased (this operation is used for discrete flows only);

– *t-displacement*: shift in time; all events are shifted in a given time interval;

– *t-compression*: compression of time; the time axis in the diagram of a flow is compressed or expanded.

Algebraic equations can be composed and solved on the bases of QTD. For instance, the current contents of the area (2+3+5+6) can be calculated as follows (see Figure 4):

$$C(2+3+5+6) = C(2) + C(3) + C(5) + C(6) =$$

$$=[T(1,2) + T(1,5)] – [T(3,4) + T(6,4)].$$

Since every QTD exists not only in the form of a graph but also in the form of an event protocol, QTD are well suited for the calculation of arbitrary performance indicators characterizing a process. These performance indicators can be both statistical and economic.

On the basis of QTD of type T(i,j), statistical performance indicators can be calculated for transportation links of:

– the distribution of time interval between events (shipments),

– the distribution of cargo volume in a shipment,

– the total cargo volume during an observation period.

On the basis of QTD of type C(i) statistical performance indicators can be calculated for the nodes of:

– stock level distribution,

– the distribution of time intervals between the moments of cargo arrival,

– the distribution of time intervals between the moments of cargo dispatch,

– the volume distribution of incoming cargo,

– the volume distribution of dispatched cargo,

– the total volume of incoming cargo during an observation period,

– the total volume of dispatched cargo during an observation period.

In each case, «distribution» is understood as the result of a statistical analysis comprised of:

– distribution density histogram,

– maximum and minimum values,

– mean value, estimation of mean square deviation and dispersion and

– the interval estimation of mean value.

Using appropriate normative factors makes it quite easy to calculate all kinds of costs for goods transportation or storage on the basis of event protocols and statistical performance indicators. The individual system of performance indicators, which considers events not only in material flows but also in the customer order flows, can be created on the basis of QTD for any specific supply network model.

QTD Application in a Supply Network Model

Figure 6 shows the example of a supply network model that illustrates the opportunities of applying QTD as an instrument for independent process modeling. In this supply chain, sources 1, 2 and 3 represent the goods suppliers of type A, B and C. Nodes 4, 5 and 6 represent corresponding transportation links, i.e. their current contents are equal to the volume of goods in transit. Node 12 is an abstract node introduced in the model only to estimate the total volume of goods in transit. It is assumed that there is one physical warehouse in the modeled supply chain. The stock level of this warehouse is considered by node 13. To this end, the stock levels of goods A, B and C set separately in nodes 7, 8 and 9 respectively are totaled. The output links of the structure are constructed on the assumption that customers 1 and 2, modeled as drains 10 and 11 respectively, are supplied with all three types of goods: A, B and C. In order to simplify the structure of a demonstration model, only the output flows of the warehouse are shown in the model. The volume of goods in transportation links connecting the warehouse with customers are not shown. One day has been chosen as a time unit in the QTD.

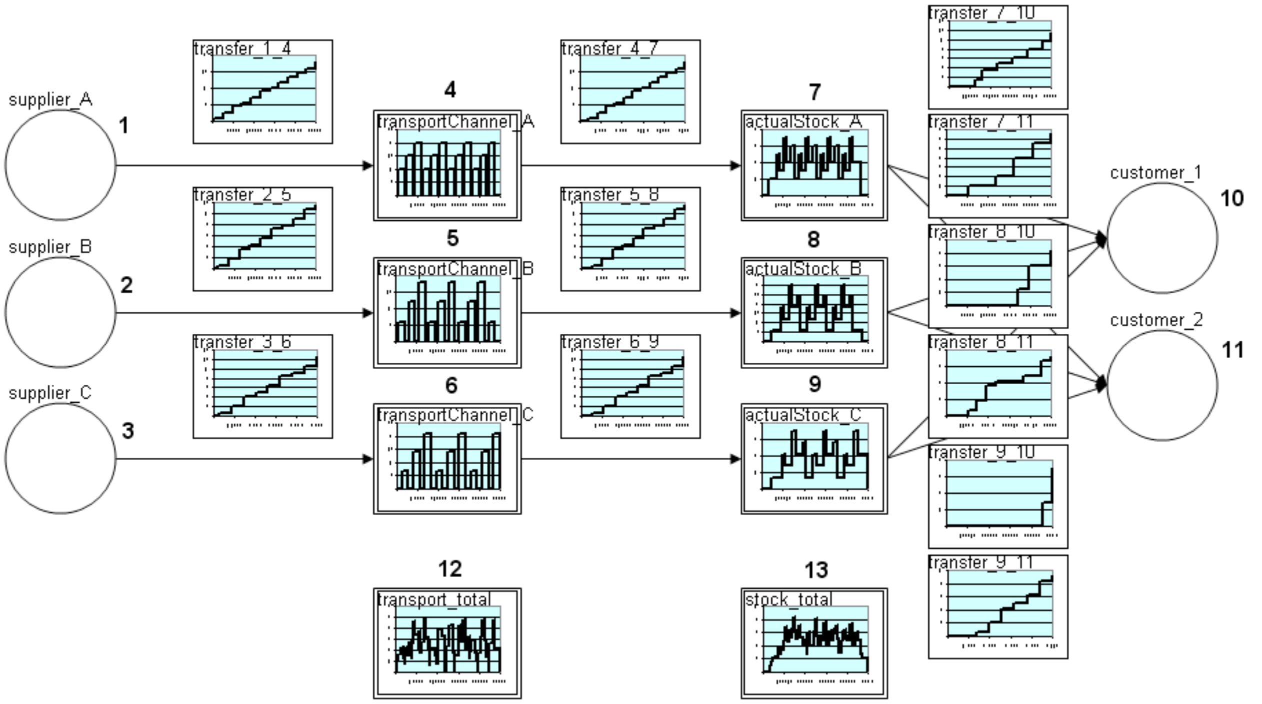


Figure 6 – Supply network structure containing the complete set of QTD

Figure 6 shows the QTD for all links (the flows of type T(i,j)) and all nodes (stock levels C(i)) of the supply network, i.e. there is no difference between the initial data and the results of modeling. In fact, the task of modeling has been formulated in the following way:

Given:

a) the assumed schedules of goods shipment to the customers is in the form of processes T(7,10), T(7,11), T(8,10), T(8,11), T(9,10) and T(9,11);

b) the assumed schedules of goods shipment by suppliers is in the form of processes T(1,4), T(2,5) and T(3,6);

c) delay time in transportation links is 3 days;

d) the initial stock levels for all goods types is A0=0, B0=0 and C0=0.

Then the following have to be defined:

a) the dynamics of a stock level at the warehouse for each type of goods (the current contents of nodes 7, 8 and 9);

b) the dynamics of a stock level at the warehouse in the form of the total goods volume (the current contents of node 13) and

c) the dynamics of the total volume of goods in transit (the current contents of node 12).

To solve the task posed, a sequence of operations automatically interpreted by «the calculator of processes» has been devised (Figure 7). This calculator was designed as a VBA macro. The duration of process modeling is 64 days. Using the operand value of 3, transportation time in transportation links (3 days) modeled in the form of nodes 4, 5 and 6 is incorporated in the model. Notation M(1) relates to a memory cell in which the acquired result is stored temporarily. Figure 7 illustrates how, in order to calculate all basic and additional QTD for each of the three goods types, it is necessary to execute four operations. The last four operations shown in Figure 7 are used to calculate the current contents of nodes 12 and 13.

Thus, the process of solving the task of modeling a supply chain by directly interpreting QTD consists of two steps:

a) QTD for given processes are created and

b) the sequence of «algebraic» operations for calculating QTD, in which an analyst is interested, is formulated and satisfied.

Certainly, this procedure can be repeated repeatedly until the moment when an analyst is satisfied with all observed QTD. The formal sign of an invalid variant of the organization of a material flow in a supply chain is the appearance of negative stock level values.

MaxTime	.=.	64		
T(4,7)	.=.	T(1,4)	t-displacement	3
C(4)	.=.	T(1,4)	subtraction	T(4,7)
M(1)	.=.	T(7,10)	addition	T(7,11)
C(7)	.=.	T(4,7)	subtraction	M(1)
T(5,8)	.=.	T(2,5)	t-displacement	3
C(5)	.=.	T(2,5)	subtraction	T(5,8)
M(1)	.=.	T(8,10)	addition	T(8,11)
C(8)	.=.	T(5,8)	subtraction	M(1)
T(6,9)	.=.	T(3,6)	t-displacement	3
C(6)	.=.	T(3,6)	subtraction	T(6,9)
M(1)	.=.	T(9,10)	addition	T(9,11)
C(9)	.=.	T(6,9)	subtraction	M(1)
C(12)	.=.	C(4)	addition	C(5)
C(12)	.=.	C(12)	addition	C(6)
C(13)	.=.	C(7)	addition	C(8)
C(13)	.=.	C(13)	addition	C(9)

Figure 7 – Sequence of operations for calculating the supply network

Conclusions

Processes in the form of QTDs can be designed in a variety of ways, for instance:

– as a result of the analytical thinking, i.e. «manually» as an intended or desirable scenario of the process;

– as a result of process observation in the real system;

– as a result of tracing functioning of the simulation model.

New, QTD-based models

– may be both discrete and continuous or hybrid;

– may be both non-stationary and stationary;

– are predominantly deterministic, but can be also probabilistic;

– use baseline data that is close to data on real processes;

– to provide give results that are far more accurate than those that may be obtained using static models;

– provide results based on which any statistical or logistic performance indicators (for example, shipping or storage costs) may be calculated;

– may be developed relatively faster than similar simulation models.

QTD can be utilized both for interpreting recorded processes and for modeling new processes. QTD-based models may take a place in the world of modeling right between analytical models applied for a rough assessment of system performance and detailed simulation models. Based on these models, qualitatively new methods for dynamic calculation of material flows may be developed, while classical models, such as queuing systems or inventory management models, will preserve their value as conceptual models.

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