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Systematic approach for designing and activities' scheduling of supply chain network

R. Adonyi[1], E. G. Kirilova[2*], N. Gr. Vaklieva-Bancheva[2]

[1]*Department of Computer Science and Systems Technology, University of Pannonia, Egyetem u. 10, 8200 Veszprem, Hungary*

[2]*Institute of Chemical Engineering, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., bl. 103, 1113 Sofia, Bulgaria*

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The present work introduces a two-level systematic approach for optimal Supply Chain (SC) Management. At the first level the SC design problem is solved by applying the mathematical programming; while at the second level the scheduling of the SC activities is modeled and solved by the S-graphs framework. The proposed systematical approach is tested on a tree echelon supply chain example. As a result both, the network of the supply chain corresponding to the optimal total site products portfolio is obtained and the optimal schedule ensuring fleet's assignments so as to implement the portfolio within the production horizon.

Key words: design, activities scheduling, supply chain, S-graph, mathematical programming

INTRODUCTION

Market globalization and increased competitiveness press plant management for a best use of available resources, efficient manufacturing, and looking for a best market position. The current manufacturing environment for process industry has changed from a traditional single-site, single market to a more integrated global production mode where multiple sites are serving a global market with multiple products. Later requires coordination of the planning across sites in terms of cost and market effectiveness [1].

In a way the correct product to be produced and delivered on time on the market, a sequence of functions called Supply Chain has to be performed. It encompasses purchasing of raw materials, transformation of these materials into intermediate and target products and distribution of these products to the customers. Some of these functions in most of the companies are performed by separated organizations which have own objectives and operate independently. Supply chain management is a strategy through which an integration of these functions is achieved. It also coordinates all input/output flows (of materials, information and funds) so that products are produced and distributed in the right quantities, to the right locations, and at the right time. Its main objective is to achieve acceptable financial returns together with the desired consumers' satisfaction.

The Supply Chain Management (SCM) problem may be considered at different levels depending on the types of decisions which should be made. The strategic decisions are made typically over a longer time horizon. These are closely linked to the corporate strategy and guide supply chain policies from a design perspective. On the other hand operational decisions are made over a day-to-day basis in short-term scheduling the SC activities.

In order to provide quantitative support for making these decisions numerous model-based approaches and algorithms have been developed. They are heuristic [2] or mathematical programming approaches [3, 4]. The proposed various deterministic models of the supply chain are formulated in terms of MINLP [5–10] or MILP [11–13]. In the case of the uncertainty in the supply chain optimization stochastic analytical models [14, 15] and scenario planning [16, 17] are used.

Usually, the SCM problem considers both, the design and scheduling decision levels. The design problem arises from the network characteristics of SC and is connected with a production planning, while the scheduling one comes from the production control.

Considered SCM problem comprises three echelons SC, i.e. sets of suppliers of raw materials, the production complex with a given number of plants manufacturing the same group of products and the group of markets (see Figure 1). The management process involves conducting the following activities: purchase of the raw materials

* To whom all correspondence should be sent:
E-mail: eshopova@mail.bg

from suppliers and their transportation to the plants, production of target products and their shipment to the markets and selling.

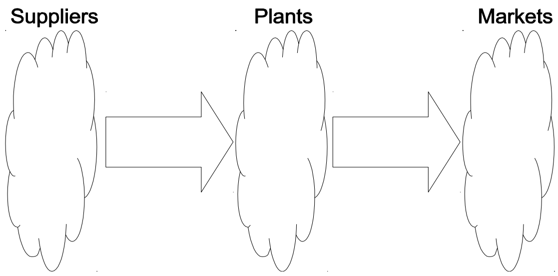

Fig. 1. The considered three echelon SC.

Accounting for the considered set of target products, the SC design problem is connected with definition of these production routes through the SC from the suppliers to the markets that results in optimal product portfolios for the entire production complex, i.e. that maximize a total income of the complex and fulfill predetermined conditions for suppliers, plants and markets in a given time horizon, Figure 2.

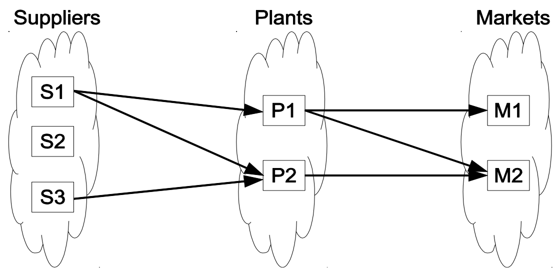

Fig. 2. Material flows in the SC network (design).

The scheduling of the SC activities comes into account after the selection of the SC network. The scheduling of the SC resources, e.g. transportation, units, is based on the parameters of the selected SC network (see Figure 3). Scheduling controls the activities of the SC elements through the transportation of raw materials and target products.

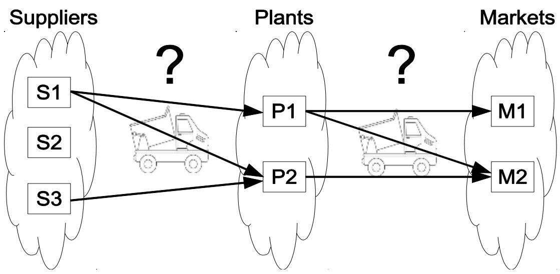

Fig. 3. Scheduling the SC activities.

The major challenge of the SCM problem is that it becomes computationally intractable when the number of production sites, markets, and products increase in the supply chain network. A good way to deal effectively with the increasing complexity is application of a sequential solution approach by using specific hierarchical methods and techniques.

The main aim of this paper is developing of two-level systematic approach for short-term SC designing and scheduling of supply chain activities, embedding continuous plant complex. The proposed approach is based on the applications of the mathematical programming approach and S-graphs framework. Firstly, for the SC design purpose, the mathematical model is built and used in an optimization framework to determine the network for the optimal total site product portfolio together with respective flow rates of the raw materials and the products. Then the S-graph framework is used for scheduling of SC activities.

FIRST LEVEL – SUPPLY CHAIN DESIGN

Firstly using a mathematical programming approach a SC design problem, is solved, defining the network with regard to the optimal total site production portfolio, and accounting for distribution of raw materials to the plants, products processing, distribution and selling of the manufactured products to the markets.

To formulate the SC design problem the alternative production routes for the demands must be considered (see Figure 1 and 2). The decision problem determines the flow rates of the raw materials and the products that have a maximal profit.

2.1. Problem description

A complex of continuous plants, set *I*, is considered. Range of products, set *p*, could be manufactured in each plant using separate production lines. Respective production rates are known. Production costs for products are constant over the time but different for each plant.

Set *J* contains the required raw materials (e.g. *j1*, *j2*). The products can be manufactured by alternative raw materials. However, only one raw material type is taken into account in manufacturing of each product but each raw material can be used for production of more than one products. No stocks and raw materials accumulations are permitted in the plants. The raw materials are provided by suppliers, set *S*, the products are transported to the markets defined by set M.

The distances between suppliers, plants and markets are known. Transportation costs depend on the raw materials and products. Transportation costs, products and raw materials costs are also known and constant over the planning horizon H. Market demands and raw materials provisions are fixed for the horizon.

Assuming that a structure of the supply chain under consideration is constant over the horizon H the goal of this step is to design it in such a way so as to define the optimal products portfolio for the total site and its distribution on the involved plants; and to determine respective routes of products from the suppliers to the markets.

2.2. Data required

To define the problem following set of data must be given:

$PRC_{i,p}$ - production cost of product p in plant i, [CU / ton];

$MDem_{m,p}$ - demand of product p on market m for the horizon H, [tons];

$Cost_{m,p}$ - cost of product p on market m, [CU per ton];

$MSup_{s,j}$ - capacity of the supply center s with regard to raw material j for the horizon H, [tons];

$CRM_{s,j}$ - cost of raw material j in the supply center s, [CU per ton];

$MDis_{i,m}$ - distance between plant i and market m, [km];

$TMC_{p,i,m}$ - transportation cost of product p between plant i and market m, [CU per ton per km];

$SDis_{i,s}$ - distance between plant i and supply center s, [km];

$TRC_{j,i,s}$ - transportation cost of raw material j from the supply centre s to plant i, [CU per ton per km].

Following additional data, concerning production rate of each plant to each product and average products yield of each product, must be given:

$PR_{i,p}$ - production rate of product p in plant i, [ton/hour].

$YF_{p,j}$ - average yield of product p in plant i from a unit mass of raw material j, [ton product /ton raw material].

2.3. Mathematical modeling of Supply Chain Control Variables

To describe the problem we introduce next groups of control variables:

Purposing to determine the structure of the supply chain two sets of binary variables are set up. Variables χ to structure the SC between the plants and markets:

$$\chi_{m,i} = \begin{cases} 1 - \textit{if market } m \textit{ is connected} \\ \quad \textit{with plant } i \\ 0 - \textit{othewise} \end{cases}, \tag{1}$$

and variables γ to structure the SC between the plants and supply centers for raw materials:

$$\gamma_{s,i} = \begin{cases} 1 - \textit{if the supply center } s \textit{ is connected} \\ \quad \textit{with the plant } i \\ 0 - \textit{otherwise} \end{cases}. \tag{2}$$

Additionally, purposing to follow for the product flows from plants to markets and for the raw materials flows from supply centers to plants we introduce following two groups of continuous variables. Variables $X_{i,p,m}$ track for the amount of product p processed in plant i and sold on market m, to be in the following boundaries:

$$0 \le X_{i,p,m} \le MDem_{p,m}, \quad \forall i, \forall p, \forall m, \tag{3}$$

and variables $Y_{i,j,s}$ accounting for the amount of raw material j bought by plant i from the supply center s, varying in:

$$0 \le Y_{i,j,s} \le MSup_{j,s}, \quad \forall i, \forall j, \forall s. \tag{4}$$

Mathematical description of Supply Chain design problem

The mathematical description of SC design problem involves a set of aggregated plants models and a set of constraints. Accounting for relations between plants and other elements (markets and supply centers) of the SC, the aggregated plants' models aim to describe the proper boundaries of the feasible product portfolio for each plant. The posed set of constraints has to track for keeping the posed conditions on the markets and in the supply centers.

Aggregated Plants' Models. To define the products portfolio for each plant i, the variables $QP_{i,p}$ are introduced to calculate the amount of each product p processed in the plant within the horizon *H:*

$$QP_{i,p} = \sum_{m=1}^{M} X_{i,p,m}\chi_{m,i}, \quad \forall p, \forall i. \tag{5}$$

From the other side, equations (5) present the condition that no stocks accumulation takes place in each plant:

Using the average yield for each product p, the amount of raw material $QRM_{i,j}$ required for its processing in the plant i is determined:

$$QRM_{i,j} = \sum_{p=1}^{P} \frac{1}{YF_{p,j}} QP_{i,p}, \quad \forall i, \forall j. \tag{6}$$

Moreover, calculated amount of raw materials $QRM_{i,j}$ must be:

$$QRM_{i,j} = \sum_{s=1}^{S} Y_{i,j,s}.\gamma_{s,i}, \quad \forall i, \forall j. \tag{7}$$

Equations (7) describe pre-posed condition for no raw materials accumulation in the plants.

Constraints. Aggregated plants' models are completed with sets of constraints tracking for product portfolio feasibility and for feasibility of the connected with the plants flows.

The product portfolio feasibility constraints ensure that the amount of each product p manufactured during the horizon H in each plant i corresponds to the plant's capacity:

$$0 \le QP_{i,p} \le PR_{i,p}\, H, \ \forall p, \forall i. \tag{8}$$

The flows feasibility constraints guarantee that the assigned to a given plant i product ($X_{i,p,m}$) and the raw material ($Y_{i,j,s}$) flows are really existing, i.e. the respective connections between the plant i and market m and supply center s exist:

$$0 \le X_{i,p,m} \le MDem_{p,m}.\chi_{m,i}, \quad \forall i, \forall p, \forall m, \tag{9}$$

$$0 \le Y_{i,j,s} \le MSup_{j,s}.\gamma_{s,i}, \quad \forall i, \forall j, \forall s. \tag{10}$$

Posed on each market m constraints ensure that the amount of product p processed in all plants and sold on it is less or equal to its demand:

$$0 \le \sum_{i=1}^{I} X_{i,p,m}.\chi_{m,i} \le MDem_{p,m}, \quad \forall p, \forall m, \tag{11}$$

Similarly, the constraints posed on each supply center guarantee that the raw material- j bought by plants from the supply center s is less or equal of its capacity:

$$0 \le \sum_{i=1}^{I} Y_{i,j,s}.\gamma_{s,i} \le MSup_{j,s}, \quad \forall j, \forall s. \tag{12}$$

Objective Function

The profit of the production complex is used as an objective function. It is determined as a difference between the incomes from products sale on the markets and expenditures for products processing, transportation and raw materials:

$$F = \sum_{i=1}^{I} \left[\begin{array}{l} \sum_{m=1}^{M}\sum_{p=1}^{P} X_{i,p,m}.\chi_{m,i} \cdot Cost_{m,p} - \sum_{p=1}^{P}\sum_{m=1}^{M} X_{i,p,m}.\chi_{m,i} \cdot PRC_{i,p} \\ - \left(\begin{array}{l} \sum_{s=1}^{S}\sum_{j=1}^{J} CRM_{j,s} \cdot Y_{i,j,s} \cdot \gamma_{s,i} + \sum_{j=1}^{J}\sum_{s=1}^{S} Y_{i,j,s} \cdot \gamma_{s,i} \cdot TRC_{j,i,s} \cdot SDis_{i,s} + \\ \sum_{p=1}^{P}\sum_{m=1}^{M} X_{i,p,m} \cdot \chi_{m,i} \cdot TMC_{p,i,m} \cdot MDis_{i,m}. \end{array} \right) \end{array} \right]. \tag{13}$$

Thus formulated objective function is subject to maximization:

$$\underset{X,Y,\chi,\gamma}{MAX}(F). \tag{14}$$

Thus formulated deterministic SC model, comprises the plants aggregated models (5–8), set of constraints (9–12), sets of control variables (1-4) and the objective function (13), and results in a Mixed Integer Non-Linear Programming (MINLP) problem. Its solution gives the optimal profit of the production complex and provides the conditions at which will be reached. Moreover, using optimal values of control variables and the set of equations (5), the respective optimal product portfolios for each involved plant is determined. Values of integer variables provide the generalized structure of looked for production routes.

SECOND LEVEL – SCHEDULING THE SUPPLY CHAIN ACTIVITIES

Based on the results of the mathematical programming the S-graph framework is used to generate the optimal fleet's assignments with regard to transportation of the obtained amounts of raw materials and products between the supply centers, the plants and the markets which results in schedule with minimal makespan.

The S-graph framework [19–21] originally was developed for scheduling of production units aiming minimization of makespan. However, using the S-graph framework for SC activities scheduling the terms equipment units and tasks lose their conventional meaning. In the SC network three consecutive operations are represented. First the raw material is transported from the supplier to the plant, second the plant manufactures the product, and third the product is transported from the plant to the market. The transportation is realized by using fleets which have different speed and cost. The order of the fleet selection can affect the required free time between two transportation jobs. The manufacturing step is performed by dedicated production lines at any given plants. This SC structure can be modeled with S-graph with three consecutive tasks, representing the transportation needs and the production. Thus, in S-graph terminology, the fleets, for the transportation tasks, and the production lines, for the manufacturing task, will represent the alternative equipment units.

The mathematical programming model determines the products portfolio of the plants and the flow rates of the supply chain network. The flow rates and the available transportation fleet capacities conclude the required number of batches to be scheduled. For example, based on the solution of the mathematical programming model, raw material *r1* from supplier *S1* is transported to plant *P1*, and the product *p1* is transported from plant *P1* to market *M1*. Plant *P2* produces from the raw material from suppliers *S1* and *S3* the required products for market *M2*. If the transportation cannot be fulfilled by any of the available fleets by itself, multiple batches are required to be scheduled.

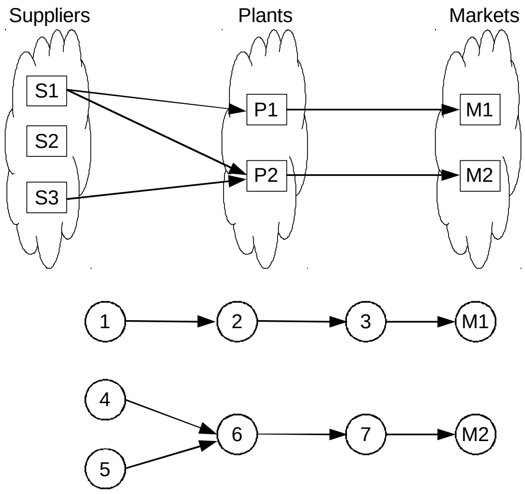

Fig. 4. Transformation of the S-graph from the results of the mathematical programming.

In Figure 4, tasks 1, 4, and 5 represent the transportations from the suppliers to the plants. Tasks 3 and 7 represent the transportation from the plants to the markets. Tasks 2 and 6 denote the production.

CASE STUDY

The efficiency of proposed approached is proved on the case study of manufacturing of four products *A*, *B*, *C* and *D* in two plants *P1* and *P2* operating in continuous mode. The products sell at two markets *M1* and *M2*. Table 1 and 2 represent demands and the incoming of the products at the markets.

Table 1. Required demands from the products at the markets.

	Demands (t)			
	A	**B**	**C**	**D**
M1	1400	55	53	110
M2	400	20	28	65

Table 2. Incomings of the product at the markets.

	Incomings (CU/t)			
	A	**B**	**C**	**D**
M1	790	1430	4530	3260
M2	900	2800	6320	3950

Two raw materials *R1* and *R2* are used for products manufacturing, which could be purchased by two suppliers *S1* and *S2*. Table 3 contains the available stocks from the raw materials at the suppliers, and Table 4 contains the prices for them.

Table 3. Available stock from the raw materials.

	Raw material stock (t)	
	R1	**R2**
S1	1800	1600
S2	850	1200

Table 4. Price of the raw materials at the suppliers.

	Price of the raw materials (CU/t)	
	R1	**R2**
S1	200	160
S2	180	140

Tables 5 – 7 contain the production rates, the cost of the production and the required raw materials for product *A*, *B*, *C*, and *D*. Plants *P1* and *P2* can manufacture the products with different cost and efficacy parameters.

Table 5. Production rates for products *A*, *B*, *C*, and *D*.

	Production rate (t/h)			
	A	**B**	**C**	**D**
P1	1	0.06	0.05	0.12
P2	0.95	0.05	0.06	0.12

Table 6. Production costs for products *A*, *B*, *C*, and *D*.

	Production cost (CU/t)			
	A	**B**	**C**	**D**
P1	165	230	165	112
P2	180	200	150	134

Table 7. Required raw materials for the manufacturing of products *A*, *B*, *C*, and *D*.

Raw material consumption (t/t)				
	A	**B**	**C**	**D**
R1	1.02	4.54	0	0
R2	0	0	20	8.33

Table 8 contains the distances between the suppliers, plants and markets. These data will be required for the calculation of the time for the transportations. For the transportations four different fleets are available with different capacities and average velocities (see Table 9). The transportation cost is based on the distance between the suppliers and plants and between the plants and markets (see Tables 10 and 11.).

Table 8. Distances between the plants, the markets and the suppliers.

Distance (km)		
	P1	**P2**
M1	226	238
M2	92	89
S1	41	31
S2	36	61

Table 9. Capacity and velocity of the available fleets for the transportation.

Fleet	Capacity (t)	Velocity (km/h)
Fleet #1	100	100
Fleet #2	300	80
Fleet #3	500	80
Fleet #4	800	60

Table 10. Transportation costs of the raw materials between the suppliers and the plants.

Transportation cost of the raw mat. (CU/t)			
Raw material	**Plant**	**Supply centre**	
		S1	**S2**
R1	**P1**	41	28.8
R2	**P1**	36.9	32.4

Table 11. Transportation costs of the products between the plants and the markets.

Transportation cost of the products (CU/t)			
Product	**Plant**	**Market**	
		M1	**M2**
A	**P1**	339	184
B	**P1**	339	184
C	**P1**	271.2	165.6
D	**P1**	271.2	165.6

RESULTS

Solution of the case study considered is carried out by using mathematical programming approach along with BASIC GA [18] optimization technique on the design level. As a result the flow rates of the raw materials and the products ensuring the maximal total site profit are obtained. Based on these results on the scheduling level S-graph framework coupled with branch and bound solution technique [19-21] is applied in order to be obtained the optimal fleet's assignments with regard to transportation of the obtained amounts of raw materials and products between the supply centers, the plants and the markets corresponding to a schedule with minimal makespan.

Besides both plants, the designed supply chain involves both markets and both distribution centers. The distribution of the materials flows between the suppliers the plants and the first and the second markets are listed in Table 12 and Table 13. On particular, they are represented the data for the purchased by the suppliers amounts of raw materials for products manufacturing and the amounts of the produced products sold at the selected markets.

Table 12. Material flows in the supply chain (products for market M1).

Supplier	Raw mat. (t)	Plant	Product to M1 (t)
S2	R1 (326)	P1	A (320)
S1	R1 (678.9)	P2	A (684)
S2	R1 (32.7)	P1	B (7.2)
S1	R2 (55.1)	P1	C (3)
S1	R2 (502)	P2	C (25.1)
S2	R2 (178.3)	P1	D (21.4)
S1	R2 (719.9)	P2	D (86.4)

Table 13. Material flows in the supply chain (products for market M2).

Supplier	Raw mat. (t)	Plant	Product to M2 (t)
S2	R1 (408)	P1	A (400)
S2	R1 (43.8)	P1	B (16.8)
S2	R1 (14.53)	P2	B (3.2)
S2	R2 (368)	P1	C (18.4)
S1	R2 (85.5)	P2	C (9.6)
S2	R2 (541.4)	P1	D (65)

Analyzing the above listed results, it can be seen that the market demands of the second market *M2* that proposes higher incomings of the products and is situated closer to both plants are completely satisfied (100%) for all four products – *A*, *B*, *C* and *D*. On a contrary, market demands of the first market are satisfied on 72% for the first product and on 13% and 53% and 98% for the second, third and the fourth products. Also greater part (60%) of the raw materials (*R1* and *R2*) required in the plant complex must be provided by the second supplier *S2*. In this way the capacity of *S2* is completely fulfilled (843.83 t from *R1* and 1200 t from *R2*) and this one of the first supplier *S1* is fulfilled up to 61%.

The optimal fleet allocation is generated by the transportations and plants scheduling. The makespan of the optimal schedule is 723.8 h. The optimal fleet assignment is given in Table 14. It can be seen that the most frequency selected fleet for transportation of raw materials and products between suppliers, plants and the markets is fleet 1 – 63%. The fleet 2 – 27% is the next one. The fleet 3 is used just one time and fleet 4 - two times.

CONCLUDING REMARKS

This study proposes two-level hierarchical approach for sequential short-term design of SC and scheduling of the activities in the Supply Chain network with embedded production complex of continuous plants. At the first level, the SC mathematical model is formulated involving aggregated plants model accounting for the connections with markets and suppliers and also for the portfolio feasibility. The model is used to determine the optimal flow rates of the raw materials and the products with regard to the maximal total site profit. From the planning level a scheduling problem is generated. S-graph framework is applied for its solution. As a result the optimal fleet's assignments with regard to transportation of the obtained amounts of raw materials and products between the supply centers, the plants and the markets corresponding to a schedule with minimal makespan are obtained.

Table 14. Scheduling the fleet.

Supplier	Raw material (t)	Plant	Product (t)	Market	
S2	R1 (326)	P1	A (320)	M1	Fleet #1
S1	R1 (678.9)	P2	A (684)	M1	Fleet #2
S2	R1 (18.8)				Fleet #3
S2	R1 (32.7)	P1	B (7.2)	M1	Fleet #4
S1	R2 (55.1)	P1	C (3)	M1	
S2	R2 (5.8)				
S1	R2 (502)	P2	C (25.1)	M1	
S2	R2 (178.3)	P1	D (21.4)	M1	
S1	R2 (719.9)	P2	D (86.4)	M1	
S2	R1 (408)	P1	A (400)	M2	
S2	R1 (43.8)	P1	B (16.8)	M2	
S1	R1 (32.5)				
S2	R1 (14.53)	P2	B (3.2)	M2	
S2	R2 (368)	P1	C (18.4)	M2	
S1	R2 (85.5)	P2	C (9.6)	M2	
S2	R2 (106.5)				
S2	R2 (541.4)	P1	D (65)	M2	

The efficiency of the proposed approach is illustrated on a case study of manufacturing of four products in production complex comprising two plants, two suppliers, and two markets. Obtained results are discussed in details.

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РЕДУЦИРАНЕ НА ПИКОВИТЕ ВЪЗДЕЙСТВИЯ ОТ ЗАМЪРСИТЕЛИ ВЪРХУ ОКОЛНАТА СРЕДА ЗА МНОГОЦЕЛЕВИ ПЕРИОДИЧНИ ХИМИЧНИ И БИОХИМИЧНИ ПРОИЗВОДСТВА

Р. Адоньи[1], Е.Г. Кирилова[2], Н.Гр. Ваклиева-Банчева[2],

[1]*Департамент по компютърни науки и системно инженерство, Панонски университет, ул. Едьетем 10,*

8200 Веспрем, Унгария

[2]*Институт по инженерна химия, Българска академия на науките, ул."Акад. Г. Бончев", бл. 103, София 1113, България*

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(Резюме)

Това изследване представя един системно-ориентиран подход за редуциране на пиковите въздействия от замърсители върху околната среда за периодични химични и биохимични производства чрез подходящо управление на стартовите времена за производство на продуктите в производствените системи. Този подход въвежда оригинални екологични оценки за въздействие на пиковете, които отчитат само тези от моментни стойности на въздействие, които надвишават определено гранично ниво и позволяват обединяването на различни типове замърсители чрез средата, в която се излъчват. Тези оценки са използвани като оптимизационни критерии във формулираната задача за редуциране на пиковите въздействия върху околната среда от периодични химични и биохимични производствени системи.

В резултат на нейното решаване са получени най-подходящите стартови времена за производство на продуктите в даден времеви хоризонт. Ефективността на подхода е показана на пример от млечната индустрия.