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OPTIMIZATION OF CAPACITY IN AN INTANGIBLE PRODUCTION

O. Zaikin(1), A. Dolgui(2), E. Kushtina(1), P. Korytkowski(1)

[1]*Szczecin University of Technology, Poland;*
[2]*Ecole Nationale Supérieure des Mines de Saint Etienne, France*

The paper addresses the problem of capacity planning for a production system of intangible products that can be interpreted as an open queuing network. The capacity is controlled through a number of parallel uniform servers and buffer capacity at each processing node. More specifically, an optimization model is presented that complies with resource utilization, production cycle, and cooperation levels under budget constraints. The proposed heuristic algorithm combines analytical modeling with discrete-event simulation. The approach is illustrated by a printing industry example.

ОПТИМИЗАЦИЯ ПРОИЗВОДИТЕЛЬНОСТИ ОБРАБАТЫВАЮЩИХ МОЩНОСТЕЙ В НЕМАТЕРИАЛЬНОМ ПРОИЗВОДСТВЕ

О. Заикин(1), А. Долгий(2), Е. Куштина(1), П. Коритковский(1)

(1)*Технический университет, г. Щецин, Польша*
(2)*Высшая горная школа в Сент-Етьен, Франция*

Рассмотрена задача планирования загрузки производственной системы, “сырьем” которой служат продукты интеллектуальной деятельности, поступающие в цифровой форме. Показано, что такая система может быть представлена в виде открытой сети массового обслуживания. Производительность системы контролируется с помощью ряда однотипных параллельных серверов и буферной емкости каждого узла обработки. Представлена оптимизационная модель, описывающая использование ресурсов, производственный цикл и уровни кооперации при бюджетных ограничениях. Предложен эвристический алгоритм, сочетающий в себе построение аналитической модели и имитационное моделирование дискретных событий. Полученные результаты проиллюстрированы примером из полиграфического производства.

INTRODUCTION

In this paper we address the problem of determining capacity levels in an intangible production. Insufficient capacity can cause elongation of production cycle that leads to late deliveries and high levels of work-in-process. Excess capacity is a waste of expensive resources due to low utilization of equipment. The problem is complicated further by the stochastic behavior of the production system like unpredictable time of orders arrival. To take into account the random behavior manufacturing systems are often modeled and analyzed using queuing network theory [1—3].

To provide a decision making tool that takes into account capacity costs and the tradeoff between cycle times, performance and cooperation, we formulate a capacity optimization model that involves minimizing capacity costs while satisfying a set of systems constrains.

Development in means of communication and digital data exchange leads to establishment of new kind of goods — intangible products [4]. Increasing computerization of manufacturing processes caused appearance in various areas for example: banking, printing and publishing, entertainment, advertisement and many others new type of manufacturing — intangible production. For this kind of production particularly arise problem of resource capacity optimization because high competitive market, close relationships with customers, high cost of equipment, etc.

An intangible product is a good that possesses a digital form, which is a direct result of an intellectual work of a man. An intangible product could be materialized through its recording or printing. The fact of materialization does not change its content, but the form of distribution.

An intangible production is an advanced manufacturing, where input materials, semi products and final products are in digital form. Manufacturing and distribution of work articles is realized with broad use of telecommunication and computer networks. It enables to establish a production process with technological operations that are distributed geographically and dynamic assignment of works between workstations. One of the main peculiarities of the intangible production is the fact that there are no mechanical operations, excluding final stages of technological process, when for example the product is printed or burned on CDs. Intangible production is usually a multi product one. Within one manufacturing system wide nomenclature of final products are produced basing on the same communication infrastructure and workstations. Intangible production is a customer oriented one. It gives unique possibility to customize all final products according to customer requirements if the company is capable of introducing it.

Described properties of intangible production enable to characterize a manufacturing process as a network of sets of work stations called later *processing nodes*. The network consists of processing nodes and telecommunication channels that connect them and enables to exchange semi-finished articles. Traffic inside the production network due to its multi product character is a mixture of traffic that is generated by a production process of each kind of final products. Network of intangible production may be represented as a *digraph*. The vertices of the digraph are the *processing nodes* and the arcs are *workflows*. Listed features of the production network give a possibility to circumscribe it as a network:

— with stochastic workflows of semi finished articles,

— unified work stations that could service several types of products.

Under term of a processing node we understand a set of uniform work stations performing the same technical operation with an input buffer that stores semi articles before sending them to one of the working posts. Output capacity of processing node is a sum of productivities of each workstations being its part. Productivity of a workstation is a number of semi finished articles that could be processed during a period of time. Processing node can be interpreted as a queuing system with parallel servers.

In an intangible production a buffers that are placed at each processing nodes should be rather considered in terms of time than space or volume. In this case articles and semi-finished products are in digital form; it means they don't have dimensions and weight. Nowadays data carriers are cheap, so it's not a problem to store semi-finished products. The challenge is to produce faster and faster. In order to do so we are considering a buffer as a source of a time loss that is wasted on waiting for servicing and we ought to avoid them. Waiting times in manufacturing are very common and probably they are inevitable. One of the methods to deal with this problem is to devolve some works to another cooperating with as company that is capable of performing that particular technological operation. It's obvious that we could not pass a lot of works other company. The tradeoff in this case is between the cycle time and the resource utilization level. The increase of cooperation will lower the cycle time; the decrease will hoist the utilization. The level of cooperation can be modeled by limitation of buffer capacity. The buffer overflow indicates the need for cooperation.

That leads us to laying down objectives of capacity planning in an intangible production:

— minimize capacity costs;

— minimize cycle time;

— minimize of jobs rejection.

The objectives depend on the number of servers and buffers capacity in an opposite way: while the number of servers increases the cycle time is falling and the idle time of servers rises. In turn while the buffer capacity increases the cycle time is rising and the costs of cooperation are reduced.

Let's introduce two constrains:

a. the network's construction costs cannot exceed the given budget;
b. capacity of each processing node must be sufficient to serve an average workflow that is directed to it.

Before discussing the capacity planning problem further, we need to define some queuing network terminology. A manufacturing system can be considered as a queuing network that consists of processing nodes where works are routed from one node to another to obtain necessary processing. As comes off production processes queuing network is an open one with deterministic routing.

The formulated task if considered as Marcovian processes of arrival and servicing can be easily solved using the Burke's Theorem [5] and decomposition of the network into separate processing nodes. However, the problem becomes more complicated when the arrival and servicing processes are given in a general form. In this case the Burke's theory is not working any longer and the optimization task requires combined usage of analytical modeling and simulation [6, 7].

1. PROBLEM STATEMENT

Below we formalize the task of performance optimization for a given structure of a supply chain.

Given

$U = \{u_i\}$ — a set of products manufactured at the production network;

$F = \{f_i\}$ — a set of flow processes (works), corresponding a set of product;

$\Pi(f_i)$ — parameters of the flow process f_i:

Λ_i — arrival pattern (distribution law);

λ_i — rate of arrival;

$L = \{l\}$ — a set of processing nodes of the production network;

$R = \{r_l\}$, $l = \overline{1, l^*}$ — kinds of equipment (servers), corresponding to the set of production network $\{l\}$;

$W(u_i) = (w_{i1}, w_{i2}, ..., w_{ij}, ..., w_{il})$ — the chain of technological operations for manufacturing the product u_i, where w_{ij} is j-th technological operation in the chain $W(u_i)$;

$\Pi(w_{ij})$ — parameters of a technological operation w_{ij}:

$r(w_{ij}) \in R$ — kind of equipment;

$\tilde{\tau}(w_{ij})$ — the average operational time.

Find

m_l, $l \in L$ — the number of units of each kind of equipment (servers, operating in parallel);

b_l, $l \in L$ — the input buffer capacity of each kind of equipment (maximal queue length in the processing node $l \in L$).

Provide

The minimum of the criterion function — total production costs for the period of optimization, which were caused by the delay of works in the production network C_1, idle time of servers C_2 and the loss of works due to of the overflow of the input buffer in the processing nodes C_3:

$$\Phi = C_1 + C_2 + C_3 + \sum_{f_i \in F} \lambda_i \sum_{w_{ij} \in \vec{W}_i} \{\tilde{T}(w_{ij}) + \tilde{\tau}(w_{ij})]\alpha_i +$$

$$+ \sum_{r_l \in R} m_l(1 - \rho_l)\beta_l \sum_{f_i \in F} + \lambda_i \sum_{l \in L} \delta_{il} Q_3^l \gamma_l = \min,$$

where $\tilde{T}(w_{ij})$ and $\tilde{\tau}(w_{ij})$ are the average waiting time and servicing time for the technological operation w_{ij}, α_i is the cost of the delay of a work u_i per a time unit, ρ_l is the utilization of an equipment (servers) at a processing node $l \in L$, β_l is the cost of an idle state of a server (unit of equipment r_l) at a processing node $l \in L$, γ_l is the cost of the loss of jobs caused by the rejection of servicing at a processing node $l \in L$, Q_3^l — is the probability that the processing node l will be blocked due to of the overflow of the input buffer,

$$\delta_{il} = \left\{ \begin{matrix} 1 \text{ if } l \in W(u_i) \\ 0 \text{ otherwise} \end{matrix} \right\} \text{ is the Kronecker's symbol.}$$

Restrictions of the task

Restriction on minimal throughput of processing nodes

$$m_l \geqslant \sum_{f_i} \frac{\delta_{il}\lambda_i}{\tilde{\mu}_l}, \quad l = 1, 2, ..., l^*, \tag{1}$$

where $\tilde{\mu}_1 = \dfrac{\sum\limits_{f_i \in F} \lambda_i \delta_{il}}{\sum\limits_{f_i \in F} \lambda_i \tilde{\tau}(w_{ij}) \delta_{il}}$ is the average rate of servicing for the processing node $l \in L$.

Restriction on maximal budget of processing nodes. This means that network's construction costs cannot exceed the given budget C_4:

$$\sum_{l \in L} m_l c_l \leqslant C_4. \tag{2}$$

The criterion function Φ is composed of three components: the component C_1 defines the quality of service from customer's point of view, the components C_2 and C_3 define the costs of servicing from the manager's point of view. These components depend on the control parameters in the opposite way. Therefore, it is possible to define such values of the control parameters, which would provide the minimum of the criterion function

$$\Phi = C_1 + C_2 + C_3 = \text{Min}\{(m_l, b_l), l = 1, 2, ..., l^*)\},$$

within a given constrains (1) and (2).

The formulated task refers to the integer-programming problem with a non-lineal criteria function and constraints.

2. SOLUTION METHOD

The formulated problem is a discrete optimization task. In [8] the algorithm, based on the Branch and Bound method is proposed. However, for a network of great dimensions the exact method can be difficult. In this paper the approximated algorithm of solution is proposed, which is based on search and identification the most loaded processing node. It is considered as a bottleneck of network.

For a general network structure and a general kind of arrival and servicing processes the task for the bottleneck search in a closed form can be difficult or even insolvable. Hence we use simulation approach to search for the bottleneck. When the bottleneck of network is known, we extent it using an analytical method. The next step is verification of the analytical solution through the simulation.

The stages of the solution method are represented below.

1. Setting the initial state of the control parameters

We consider the flow processes arriving to each processing node as independent ones. This gives the opportunity to set up the initial values of the control parameters $\{(m_l^0), (b_l^0)\}$, $l \in L$ at each node, as following:

— the initial capacity of buffers at each node is infinite $b_l^0 = \infty$;

— the number of servers (m_l^0) is set by using the condition of balance between rates of the arrival and servicing at each node [9, 10]

$$m_l^0 = \sum_{f_i} \frac{\delta_{il}\lambda_i}{\tilde{\mu}_l}.$$

2. Simulation of the stochastic process in the production network

The simulation gives great possibilities for analyzing and verification of the stochastic process, because has no restrictions for the structure and dimension of the production network, the kind of arrival and servicing patterns and the servicing discipline [11, 12].

The simulation model was constructed under the following conditions:

- the production network consists of an optional number of processing nodes;
- the streams arriving the production network have different parameters (distribution law and rate of arrival);
- each processing node represents a multi-channel queuing system with identical servers, operating in parallel;
- the capacity of the input buffer is unlimited;
- the discipline of servicing is 'First come-First served'.

3. Search for a bottleneck in a queuing network

The simulation model allows defining the variables for each processing node:

— the average system-through flow time of a job;

— the utilization and idle time of servers in a processing node;

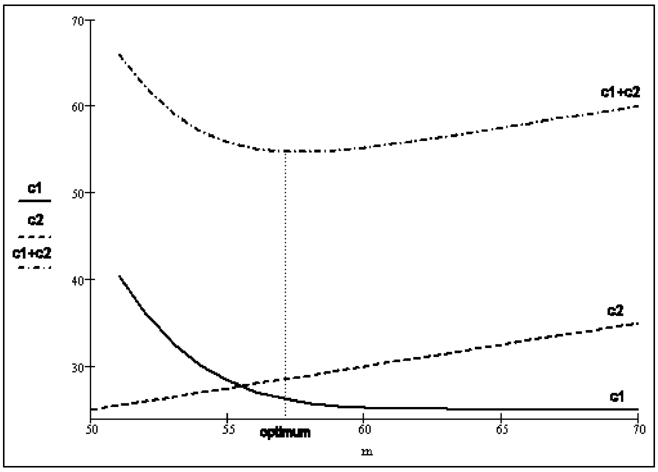

Fig. 1. Relationship between the flow time and idle time of servers depending on number of servers

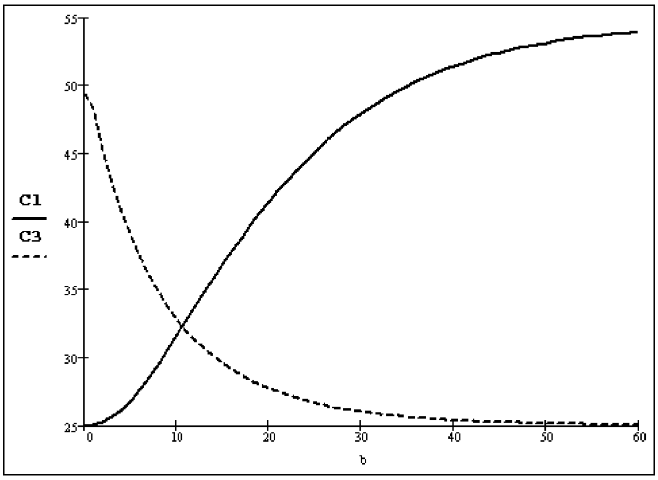

Fig. 2. Relationship between the flow time and rate of jobs rejections depending on buffer capacity

— the loss of works due to of the overflow of the input buffer in the processing nodes.

Hence the value of the criterion function Φ_l can be calculated basing on the mentioned variables for each processing node. Therefore among all processing nodes we can select one, which has the maximal value of the criterion function

$$\Phi_l = C_1^l + C_2^l + C_3^l = \text{Max}, \quad l = 1, 2, ..., l^*.$$

Evidently here the arriving works have the biggest production cost and we can consider this processing node as 'bottleneck'.

4. Local optimization on the basis of analytical modeling

The goal of this stage is the 'extension' of discovered 'bottleneck'. This extension consists in optimization of the control parameters of the processing node, providing the minimal value of the criterion function

$$\Phi_l = C_1^l + C_2^l + C_3^l = \text{Min}(m_l, b_l), \quad l \in L,$$

taking into consideration the given constraints

$$m_l \geqslant \sum_{f_i} \frac{\delta_{il}\lambda_i}{\tilde{\mu}_l}, \tag{3}$$

$$m_l c_l \leqslant C_4^l. \tag{4}$$

This optimization is realized on the base of method, described in [13], where the analytical model of an isolated processing node a kind of M/M/m/N is represented.

The dependence of criterion components C_1 and C_2 on number of servers m is shown in fig. 1, the dependence of variables C_1 and C_3 on size of input buffer b is shown in fig. 2. As follow these variables depend on parameters $(m_l b_l)$ in the opposite way. With the growth of the number of parallel servers m_l the flow time $C_1(m_l)$ falls and the production costs $C_2(m_l)$ caused by the idle-state rises. On the other hand, with the reduction of the input buffer capacity b_l the flow time $C_1(b_l)$ falls and the costs $C_3(b_l)$, caused by the loss of jobs, rises. Therefore, we can find the optimal values of the control parameters (m_l, b_l) that provide the minimum of the criterion function $\Phi = C_1 + C_2 + C_3$ and satisfy the constraints (3) and (4).

5. Simulation and verification of modeling and optimization

At this stage the verification of the analytical modeling and the optimization is done via simulation. The advantage of the proposed method is the possibility of completing the algorithm at any step of the performance. For this goal the following cycle is organized in an algorithm:

1) simulation of the production network and definition of performance measures;
2) calculation of the current value of the criterion function Φ for the entire supply chain;
3) checking the constraints (1) and (2):
   - — if the constraints are satisfied, then the algorithm is completed;
   - — if not satisfy, then transition back to point *4* is realized: search for the next processing node being the bottleneck.

3. ILLUSTRATIVE EXAMPLE

Let's consider the task of performance optimization for a publishing production network. A typical example of a publishing production network is a prepress centre, which includes a set of specialized workplaces: the flatbed or drum scanners, the power graphic station for image processing, the raster image processor (RIP), the image setter, and the color proofing unit. The incoming workflow of customer's demands corresponds to a certain kind of publication, characterized by the kind of information (text, graphic, illustration) and the set of technical parameters (format, colors, screen line number). The technological route is organized at the pre-

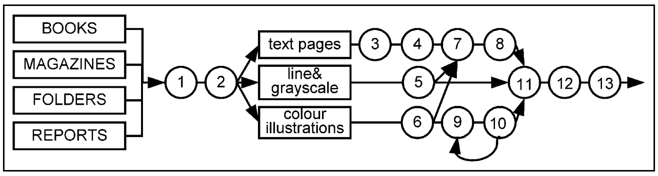

Fig. 3. Technological graph of the prepress process

Table 1

Characteristics of technological operations

N	Type of operation	Operational time (min/page)
1	Project's design within the client's budget	10*
2	Publication design	40*
3	Text edition	2
4	White and black images scanning	10
5	Colour images scanning	4
6	Composition	2
7	Design proof	1
8	Image-processing (colour correction, colour separation)	10
9	Colour image proofing	5
10	High-quality camera-ready art, suitable for negative-plate production; imposition of publication	10
11	Image processing	5
12	Film Negative Making	15
13	Plate Making	40*

* Time for a whole publication

press centre for each kind of publications. Each processing node has several equipment units of a certain kind.

The technological graph for the prepress stage of the publishing process is presented in Figure 3. As it is shown in the figure there are several workflows in the publishing process, corresponding to different kinds of publications. There are four kinds of publications with different kind of the arrival pattern:

- books and booklets, which are characterized by the deterministic time of arrival and exponential time of servicing;
- periodical press, e. g. bibliographic, academic periodical publications, entertainment and commercial magazines, etc., which are characterized by deterministic times of arrival and servicing;
- occasional printing works, e. g. advertising, folders, booklets, etc., which are characterized by exponential times of arrival and servicing;
- internal publications, e.g. proceedings and reports, which are characterized by the general time of arrival and servicing.

A typical prepress process, which consists of 13 technological operations, was modeled [14]. Some characteristics of the technological operations for the prepress process, presented on fig. 3, are shown in table 1.

Basing on the developed algorithm (section 2) the model of publishing production network was optimized. To verify and to validate the proposed algorithm a simulation model was created in the general-purpose simulation software Arena 9.0 from Rockwell Software [15].

For selected tests, simulation experiments were conducted under the following conditions.

- Four independent workflows income the production network:
  - the Poisson stream of pages arrives for books and booklets;
  - the deterministic stream of pages arrives for magazines;
  - the stream of pages with normal distribution arrives for advertising folder;
  - the deterministic stream of pages arrives for annual report).
- Operational time for each kind of page (see fig. 3) is fixed, but number of pages in each kind of publication can vary correspondingly to servicing time distribution.
- The waiting queues in all processing nodes are unlimited.
- Service discipline is 'First come-First served'.
- To obtain a high quality data 12 replications were made; a length of each was 180 days i. e. 4320 hours, warm-up period was 2 days.

Let's examine the proposed optimization algorithm using the model of prepress process described above. The basing configuration of the publishing production network is shown in the table 2.

The value of the criterion function was computed for each processing node. The overall value of the criterion function for the whole prepress system in this case was about 4800. On second step of optimization algorithm 12th processing node was found as a bottleneck. The value of the criterion function for this processing node is the highest one and it's equals to 1102.6. The direct cause of it is the high level of servers utilization and long time of orders 'flow' through 12th processing node.

Table 2

Values of the criterion function for all servicing nodes

Number of operation	Number of servers	Input buffer capacity	Flow time [h]	Utilization	C_1	C_2	Φ
1	1	Infinite	1,5	0,39	8,6	64,3	137,1
2	1	The same	0,9	0,26	5,7	37,5	80,6
3	2	»	3,4	0,49	5,0	143,7	292,5
4	6	»	17,5	0,81	31,2	502,8	1036,7
5	1	»	1,1	0,33	5,7	4,3	14,3
6	1	»	1,4	0,35	5,6	14,3	34,3
7	2	»	0,8	0,37	11,3	32,4	76,0
8	9	»	7,5	0,82	46,6	319,8	686,3
9	2	»	3,1	0,48	11,0	31,4	73,9
10	3	»	6,5	0,64	16,1	66,3	148,7
11	4	»	11,3	0,93	60,3	481,4	1023,1
12	**13**	»	**10,6**	**0,85**	**196,9**	**452,9**	**1102,6**
13	1	»	0,8	0,25	20,8	35,7	92,2

Using the analytical procedure developed by [13] the optimal number of servers for the twelfth 12th processing node has been found. Table 3 presents the value of the criterion function depending on the number of servers working in parallel in the twelfth servicing node under condition that no other parameter has been changed. The conducted experiments (Table 3) showed that the optimal number of servers for the 12th operation is 16 and the input buffer capacity equal to 30.

After the first round of the optimization algorithm the bottleneck moved to the other processing node. The next discovered processing node is the 11th one. The maximal value of the criterion function for this processing node is 1100. Again this time the local optimization algorithm was applied. The optimal configuration of the 11th processing node is 7 servers and the input buffer with capacity equals to 25.

The algorithm stops when the next found processing node being a bottleneck is the same as the previous one. The final organization of the presented publishing production network is shown in the table 4.

As a result the total value of the criterion function Φ decreased on two rounds of the optimization algorithm from 4800 down to 4148, what is more than 13 %.

Table 3

A comparison of different configurations of 12th processing node

Number of servers	Flow time [*h*]	Utilization	C_1	C_2	Φ
12	11,9	0,94	180,7	531,0	1242,8
13	10,6	0,87	196,7	473,1	1142,9
14	10,0	0,80	212,8	449,0	1110,7
15	9,4	0,75	228,8	420,0	1068,8
16	**9,2**	**0,70**	**244,8**	**412,0**	**1068,7**
17	9,1	0,66	260,8	407,1	1075,0
18	9,0	0,63	276,7	403,9	1084,5
19	9,0	0,59	292,8	402,3	1097,4

Table 4

The final results and the final configuration of the publishing supply chain

Number of operation	Number of servers	Input buffer capacity	Flow time [*h*]	Utilization	C_1	C_2	Φ
1	1	Infinite	1,5	0,37	8,6	66,5	141,6
2	1	The same	0,9	0,26	5,7	39,4	84,6
3	2	»	3,2	0,48	5,0	93,2	191,5
4	6	»	17,7	0,80	31,2	519,2	1069,6
5	1	»	1,1	0,33	5,7	5,2	16,1
6	1	»	1,4	0,34	5,7	14,4	34,4
7	2	»	0,8	0,37	11,3	34,2	79,6
8	9	»	7,6	0,81	46,7	338,5	723,7
9	2	»	3,0	0,47	11,1	31,3	73,7
10	3	»	6,0	0,63	16,1	63,0	142,2
11	7	25	3,2	0,52	108,4	144,2	396,8
12	16	30	9,5	0,68	245,1	425,7	1096,4
13	1	Infinite	0,9	0,25	20,8	38,6	98,0

CONCLUSIONS AND FUTURE WORK

The conducted experiments proved good quality of the presented methodology. The obtained results are satisfying.

The problem of the resource allocation in a production network can be formulated as a task of discrete optimization of parameters in the open queuing network. The objective function of the task depends on the stochastic and deterministic parameters, such as the distribution law of the arriving works, the distribution law of the service time, the number of parallel servers and the capacity of the waiting queue in all processing nodes of the production network.

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☎ *(+4891) 449-55-08, 2 (+48) 91 449-55-40*

☎ *+33 (0)4.77.42.01.66, 2 +33 (0)4.77.42.66.66*

E-mail: ozaikine@wi.ps.pl, dolgui@emse.fr ❑