Simulation Modeling of Manufacturing System in Relation to Route Flexibility Degree, Open Rate of Operations and Production Type

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***Abstract*—In the paper the influence of route flexibility degree, open rate of operations and production type coefficient on makespan is discussed. The flexible job-open shop scheduling problem FJOSP (an extension of the classical job shop scheduling) is analyzed. For the analysis of the production process the GRASP (greedy randomized adaptive search procedure) and simulated annealing heuristic algorithms were used. Experiments with different levels of factors have been considered and compared. The presented algorithms have been tested, and illustrated with examples for serial route.**

***Index Terms*—Makespan, open shop, route flexibility, simulation modeling, type of production.**

I. Introduction

Simulation modeling [1]-[17] is a common paradigm for analyzing complex systems. The greatest overall benefit of using simulation in a manufacturing environment is that it allows a manager or engineer to obtain a system wide view of the effect of "local" changes to the manufacturing system. There are a number of specific potential benefits from using for manufacturing analyses, including [11]:

- increased throughput (parts produced per unit of time)
- decreased times in system of parts
- reduced in-process inventories of parts
- increased utilization of machines or workers
- increased on-time deliveries of products to customers, etc.

Simulation is well known as a powerful tool supporting the design, layout or re-design of production systems. Recently, many successful applications proved that it can also support the operation of manufacturing systems, especially in the area of scheduling and control.

Almost in large, and the majority of small and medium –sized enterprises run MRP/ERP systems. However, many are not satisfied with their systems.

There are a number of other well-known [18]-[25], general-purpose simulation packages, including AnyLogic [26], GPSS/H [18], HyPerformix Workbench [22], MicroSaint [23], SIMSCRIPT III [19], SIMUL8 [20],[25], SLX [21].

Several simulation products such as Simulik, ACSL, and Dymola have been specifically designed for building continuous simulation models. In addition, Discrete Event simulation packages Arena [15] and Extend [10] have continuous modeling capabilities.

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We list [27]-[33] some of the application-oriented simulation packeges that are currently available which are used in manufacturing and supply chain: Simulation Dynamics [33], AutoMod [27], Enterprise Dynamics, Flexsim [29], PROMODEL [30],[32], QUEST [28], Witness [31].

The broad goal of manufacturing operation management, such as a resource constrained scheduling problem, is to achieve a coordinated efficient behaviour of manufacturing in servicing production demands, while responding to changes on shop-floors rapidly and in a cost effective manner. Shop floor scheduling, such as resource constrained scheduling problems in general, is a combinatorially complex, NP-hard problem, thus is unfeasible to be solved computationally by the sole use of conventional operations research approaches.

The development of decision-making methodologies is currently headed in the direction of simulation and search algorithm integration. This leads to a new approach, which successfully joins simulation and optimization. Artificial Intelligence based or hybrid techniques using domain specific heuristics are necessary to guide the search and to provide satisfactory solutions in due time [34]-[42] .

The paper is organized as follows. Section 2 formulates the problem. In section 3 the dependency of makespan on the flexibility of route, open rate of operations and production type coefficient for serial route have been described. The concluding remarks are given in section 4.

II. Problem Formulation

The *n x m* classical job shop scheduling problem (JSP) involves *n* jobs and m machines. Each job is to be processed on each machine in a predefined sequence. We consider of the flexible open - shop scheduling problem.

In an open shop scheduling problem (OSP), a set of *n* jobs $I_1, I_2, ..., I_n$ has to be processed on a set of *m* machines $M_1, M_2, ..., M_m$. The processing of a job on machine is denoted as an operation, and the sequence in which the operations of a job are processed on the machines is immaterial.

Flexible job shop scheduling problem (FJSP) extends the JSP by allowing each operations to be processed on more than machine. With this extension, we are now confronted with two subtask: assignment of each operation to an appropriate machine and sequencing operations on each machine.

The FJOSP is formulated as follows. There is a set of jobs $Z = \{Z_i\}$, $i \in I$, where $I = \{1, 2, ..., n\}$ is an admissible set of parts, $U = \{u_k\}$, $k \in 1, m$, is a set of machines. Each job Z_i is a group of parts Π_i of equal partial task p_i of a certain range of production. Operations of technological processing of the i-th part are denoted by $\{O_{ij}\}_{j=\xi}^{H_i}$. Then for Z_i, we can write $Z_i = (\Pi_i \{O_{ij}\}_{j=\xi}^{H_i})$, where $O_{ij} = (G_{ij}, t_{ij\,(N)})$ is the j- th operation of processing the i-th group of parts; ξ_i is the number of operation of the production process at which one should start the processing the i- th group of parts; H_i is the number of the last operation for a given group; G_{ij} is a group of interchangeable machines that is assigned to the operation O_{ij}; G is a set of all groups of machines arose in the matrix $\|\{Z_i\}\|$; $t_{ij}(N)$ is an elementary duration of the operation O_{ij} with one part d_i that depends on the number of machine N in the group (on the specified operations); t'_{ij} is the duration of set up before the operation O_{ij}; N_{gr} is the number of all groups of machines. In this problem the sequence in which the operations of a job are processed on the machines is immaterial (with different open rates of operations). The most widely used objective is to find feasible schedules that minimize the completion time of the total production program, normally referred to as makespan (*Cmax*).

In this paper the dependency of makespan on the route flexibility degree, open rate of operations and production type coefficient for serial route have been described. The algorithm SA+GRASP [43-44] for the optimization of the production process has been used.

III. Computer Experiments

If a model has only one factor, the experimental design is simple: we just run the simulation at various values, or levels, of the factor, perhaps forming a confidence interval for the expected response at each of the factor levels.

In this experiment there are $k = 3$ factors and we want to get an initial estimate of how each factor affects the response. We might also want to determine if the factors interact with one another, i.e., whether the effect of one factor on the response depends on the levels of the others. On way to measure the effect of a particular factor would be to fix the levels of the other k-1 factors at some set of values and make simulation runs at each of two lewels of the factor of interest to see how the response reacts to changes in this single factor. A much more ecomical strategy for determining the effects of factors on the response with which we can also measure interactions, called a 2^k factorial design, requires that we choose just two levels for each factors and then calls for simulation runs at each of the 2^k possible factor-level combinations, which are sometimes called design points. Because we are using only two levels for each factor, we assume that that the response is approximately linear over the range range of the factor.

In this work we examined open job problem defined in such a way that an operation (of the same type) of a job can be performed on any machine of changeable machines group (CMG) and the sequence in which the operations are processed on the machines is immaterial. The open rate of process O was defined as the number of operations in a process can be performed with immaterial sequence. For example, let there be 10 operations for given part. If two operations can be performed on any machine in the CMG group and sequence in which these operations are processed is immaterial then the open rate is 2/10= 0.2 = 20 %. In this paper the following open rates were used O : 6 %, 13 %, 19 %, 25 %, 31 %, 38%, 44%, 50%, 56%, 63%, 69%, 75%, 81% and 100%.

The route flexibility defined in such a way that an operation of the same type can be performed on any machine of changeable machines group. The flexibility rate E was defined as the number of machines in a group capable of performing a given operation. For example, let there be 10 changeable machines divided into 5 groups of two machines. If a given operation can be performed on any machine in the CMG group, then the flexibility rate is 2/10=0. In this work the following route flexibility rates were used E : 0.2; 0.4; 0.6; 0.8 and 1.0.

We can use value of production type coefficient K_{tp}, which is described:

$$K_{tp} = \frac{\sum_{i=1}^{m} P_0 \times F \times K_0}{\sum_{i=1}^{n} N_i \times t_i} \tag{1}$$

where: $\sum_{i=1}^{m} P_0$ - general number of production operations that were used at i working position in a month, $i \in 1, m; F -$ a fund of work time in a month; N_o - an average coefficient of a norm execution; N_i monthly program of i assortment; t_i − labor of i assortment; n - a number of products assortment. With coefficient K_{tp} (further marked with the symbol k) we can show relationships between a type of process, a form of process organization, and a kind of production system technical base [45]. In a serial route an entire batch of parts is processed on one machine and only when all of the products in the batch have been processed are they sent to the next machine.

A. *Experiments* with 3 Factors *(Variant 1)*

For the experiment with one factor, the C_{max} value increased, when the open rate changed as follows: O1'-100%, O2'-44% and C_{max} value increased, when the flexibility degree changed in the following sequence: E1'-0,2; E2'-1, E3'-0,4. The experiments with the k coefficient proved that the C_{max} increased when the k value decreased as follows: k1'-32, k2'-19, k3'-7 (as shown in Table 1).

TABLE I: C_{MAX} Values for the Experiment with One Factor

Experiment	Open rate, flexibility degree, coefficient k	level sign	makespan average [min]
Open rate	0-15 (100%)	O1'	15178,42
	0-6 (44)%	O2'	40381,55
	0 (0%)	O3'	53649,13
Flexibility degree	0,2	E1'	50242,2
	1,0	E2'	50397,28
	0,4	E3'	51926,76
Coefficient k	32	k1'	24536,44
	19	k2'	27682,94
	7	k3'	50666,84

The three-factor experiments carried-out show the influence of the factors (flexibility degree E, open rate O, coefficient k) on the makespan C_{max} value (Table 2).

The experiments proved that the C_{max} values do not always increase when the open rate increases, as was the case with the one-factor experiment (in the sequence O1', O2', O3'). For the open rate O1, the C_{max} values are the lowest (regardless of the flexibility degree *E* and the *k* coefficient). However for the other two levels of the open rate, the C_{max} values depend on the *E* flexibility degree and/or the *k* coefficient.

TABLE II: C_{MAX} VALUES FOR EXPERIMENT WITH THREE FACTORS (FLEXIBILITY DEGREE, OPEN RATE, *K* COEFFICIENT)

Eksperiment	open rate level	Open rate value	Flexibility degree level	Flexibility degree value	Coofficent k level	Coofficent k value	Makespan value			
							average	change	min	max
1	O1	0-15	E1	0,2	O1k1	32	18940,8	-	18940,8	18940,8
2	O1	0-15	E1	0,2	O1k2	19	18940,8	0,00%	18940,8	18940,8
3	O1	0-15	E1	0,2	O1k3	7	19213,1	1,44%	18940,8	19572,9
4	O1	0-15	E2	1	k1	32	14063,6	-26,80%	14054,4	14071,5
5	O1	0-15	E2	1	k2	19	13458,6	-4,30%	13448,6	13472,3
6	O1	0-15	E2	1	k3	7	13066,3	-2,91%	12921,8	13273,2
7	O1	0-15	E3	0,4	k1	32	14100,7	7,92%	14065,5	14129,9
8	O1	0-15	E3	0,4	k2	19	13741,7	-2,55%	13525,9	13831,1
9	O1	0-15	E3	0,4	k3	7	14890,1	8,36%	14038,7	15612,4
10	O2	0-6	E1	0,2	O2k1	32	26413,2	77,39%	26080,3	26709,3
11	O2	0-6	E1	0,2	O2k2	19	28185,3	6,71%	27591,3	28527,9
12	O2	0-6	E1	0,2	O2k3	7	44505,2	57,90%	44378,3	44781,4
13	O2	0-6	E2	1	k1	32	21170,8	-52,43%	20957,3	21381,3
14	O2	0-6	E2	1	k2	19	24446,1	15,47%	24059,4	24721,9
15	O2	0-6	E2	1	k3	7	42790,3	75,04%	41620,9	43482,1
16	O2	0-6	E3	0,4	k1	32	23034,4	-46,17%	22866,2	23228,0
17	O2	0-6	E3	0,4	k2	19	25820,0	12,09%	25442,1	26056,2
18	O2	0-6	E3	0,4	k3	7	44100,2	70,80%	42924,0	44763,5
19	O3	0	E1	0,2	O3k1	32	28084,1	-36,32%	27738,8	28642,6
20	O3	0	E1	0,2	O3k2	19	32021,4	14,02%	31461,5	32466,2
21	O3	0	E1	0,2	O3k3	7	53358,2	66,63%	53358,2	53358,2
22	O3	0	E2	1	k1	32	22611,5	-57,62%	22511,3	22671,0
23	O3	0	E2	1	k2	19	27276,7	20,63%	26711,2	27910,9
24	O3	0	E2	1	k3	7	53923,8	97,69%	53358,2	55428,6
25	O3	0	E3	0,4	k1	32	24709,1	-54,18%	24050,8	25058,6
26	O3	0	E3	0,4	k2	19	28715,2	16,21%	28284,2	29105,1
27	O3	0	E3	0,4	k3	7	57350,3	99,72%	54612,8	59514,9

The C_{max} value is always lower for level O2 than O3, but only when we take into account the same levels of the flexibility degree and of the *k* coefficient . Therefore it can occur that with the same *k* coefficient and different flexibilty degrees, the C_{max} values will be lower for level O3 than O2 (for example: with the same k1 level the C_{max} value for O3 and E3 is lower than the C_{max} value for O2 and E1). Similarly with the same flexibility degree, the C_{max} value for the O3 open rate can be lower than for level O2, while the *k* coefficient changes.

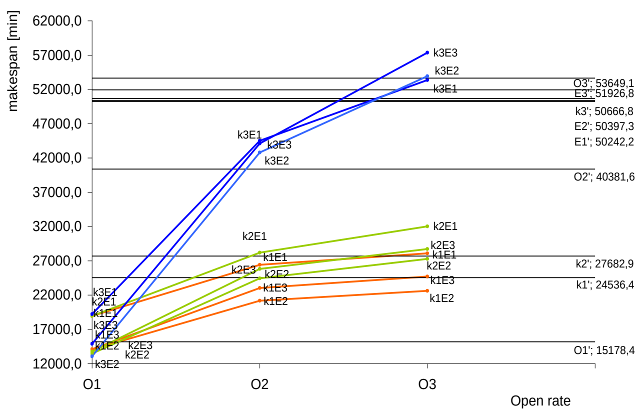

Fig. 1. Relationship between the C_{max} value and the open rate for various values of the flexibility degree and the *k* coefficient

For the experiment with one factor, the C_{max} values increased, when the *k* coefficient decreased (according with the sequence k1', k2', k3'). In case of the experiment with three factors (flexibility degree, open rate, the *k* coefficient) the C_{max} values did not increased when the *k* coefficient changed from k1 to k2 to k3. The maximum C_{max} value was obtained at the k3 coefficient level on levels O2 and O3 of the open rate. On the other hand with the same k3 coefficient – the C_{max} values are the lowest when the open rate is O1.

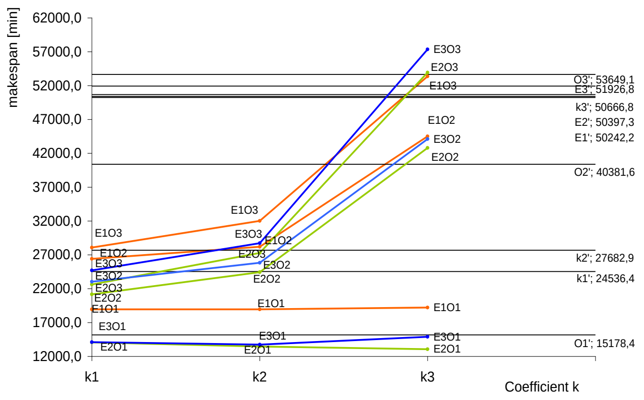

Fig. 2. Relationship C_{max} value and coefficient *k* for various values of open rate and flexibility degrees

For the experiment with one factor the C_{max} values increased when the flexibility degree is as follows: E1', E2', E3'. In the case of the three-factor experiment (flexibility degree, open rate, coefficient *k*) the C_{max} values are various for various flexibility degree levels. The average minimum C_{max} value was obtained at the E2 flexibility degree level, and the maximum C_{max} values were obtained at the E3 flexibility degree level.

Considering the minimum and maximum C_{max} values for a given flexibility degree and open rate level it can be noticed that for levels O1, O2 and O3 levels the minimum C_{max} value was obtained at the E2 flexibility degree (i.e. differently than for the experiment with one factor, where the minimum C_{max} value was obtained at the E1' level). Moreover for the O1 and O2 open rates levels the maximum C_{max} was obtained at E1 (also differently than in the experiment with one factor, where the maximum C_{max} value was obtained at the E3'), while for O3 at the E3 level.

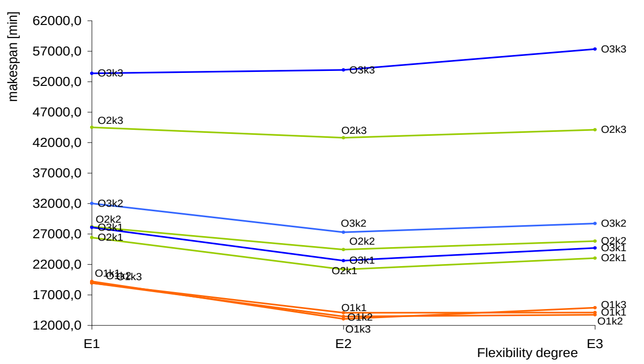

Fig. 3. Relationship C_{max} value and coefficient *k* for various coefficient *k* and open rate

The maximum C_{max} value was obtained at a combination of O3, E3, k3, and the minimum C_{max} value at the O1, E2, k3 combination. The worst result was obtained at the same combination of the factor levels as in the experiment with one factor. On the other hand the minimum C_{max} value for the experiment with three factors (flexibility degree, open rate, coefficient *k*) was obtained only for one level in the experiment with one factor i.e. at the O1 level. The other combinations proved that the C_{max} value should be worse, however the best result was obtained at the O1 level.

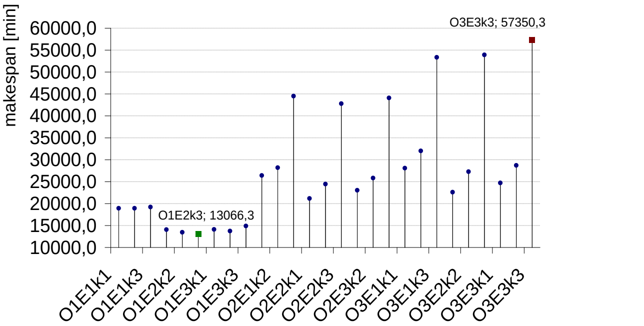

Fig. 4. Min and max C_{max} value in experiment with three factor (flexibility degree, open rate, coefficient *k*)

B. *Experiments* with 3 Factors *(Variant 2)*

Considering the fixed open rate the following relationships can be noticed (Fig. 5) For the O1 open rate level, the maximum C_{max} value was obtained for the E1 flexibility degree level, while the minimum C_{max} value - at the E2 flexibility degree level (although not in every case).

The value of the *k* coefficient does not influence the C_{max} value in a decisive way, because C_{max} values - small, medium, and large – were obtained for all levels of the *k* coefficient. For O2 and O3 open rate levels the *k* coefficient has great influence on the C_{max} value.

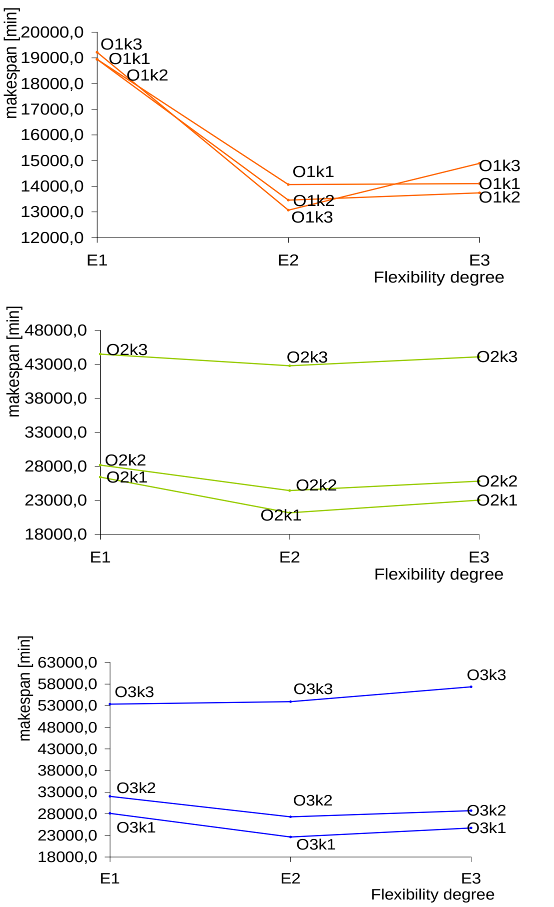

Fig. 5. Relationship between C_{max}, flexibility degree, *k* coefficient and the fixed O1, O2 and O3 open rate levels

When the *k* coefficient decreases (from k1 to k3), the C_{max} increases (as in the experiment with one factor when only the *k* coefficient is considered). The exception for the O2 open rate level is only one C_{max} value – with the combination O2, k1, E1, at which the C_{max} value is greater than the value for the k2 level, i.e. with the combinations O2, k2, E2 and O2, k2, E3. The exception for the O3 open rate level is also one C_{max} value, with the O3, k1, E1 combination, at which the C_{max} has a greater value than for the *k* coefficient, i.e. with the O3, k2, E2 combination. Most C_{max} values which are obtained at O1, O2 and O3 open rate levels are lower than the values which were obtained in one-factor experiment (O1', O2' and O3' open rate levels respectively) .

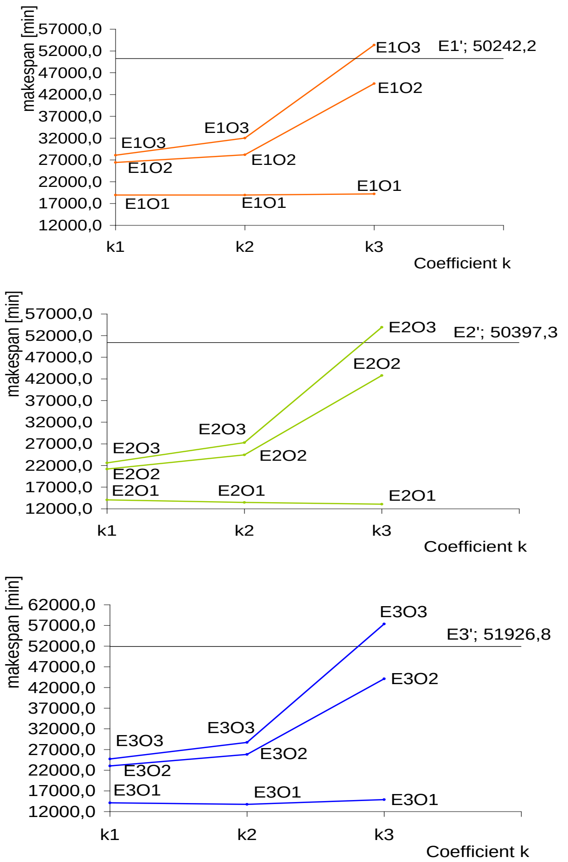

Fig. 6. Relationship C_{max}, *k* coefficient, open rate and the fixed E1, E2 and E3 flexibility degree

Considering the flexibility degree as fixed the following dependencies can be noticed (fig. 6).

Considering the *k* coefficient as fixed the following dependencies can be noticed (fig. 7).

For all *k* coefficient levels, at O1 open rate level the minimum C_{max} value was always obtained. On the other hand for the k3 coefficient, at the O3 open rate level, the maximal C_{max} value is always obtained. The flexibility degree does not influence significantly the C_{max} value, because C_{max} values - small, medium, and large – were obtained for all levels of the *k* coefficient. However it can be noticed that at E2 the minimum C_{max} value is obtained, regardless of the *k* coefficient level. Most C_{max} values obtained at k1, k2 and k3 coefficient are lower than the values obtained in the experiment with one factor (k1', k2'and k3' respectively).

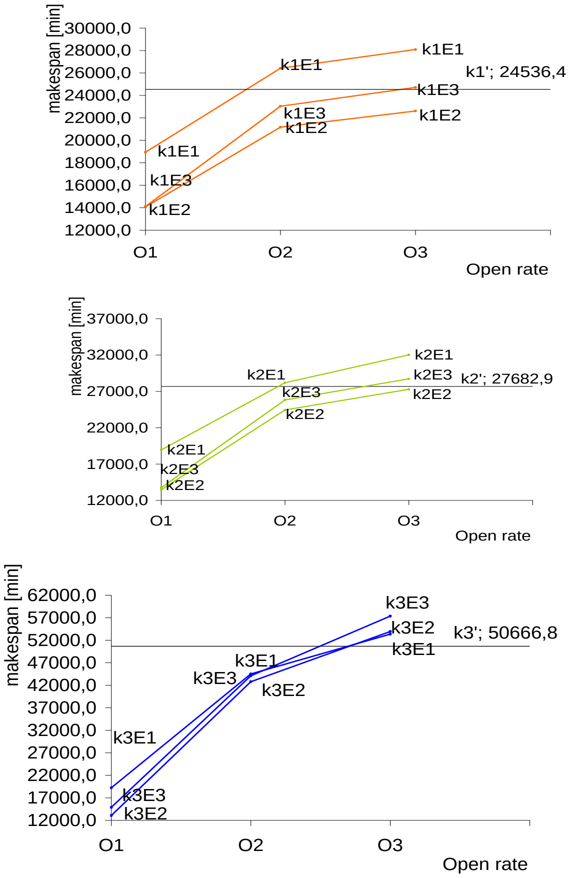

Fig. 7. Relationship C_{max} , open rate, the flexibility degree and the fixed k1, k2 and k3 coefficient.

IV. Conclusion

We proposed the use of SA+GRASP metaheuristic in the analysis of the production systems (for flexible job-open scheduling problem). The influence of route flexibility degree, open rate of operations and production type coefficient on makespan is discussed. Experiments with one and three factors have been tested and different levels of factors have been considered and compared. The algorithms have been implemented, tested, and illustrated with examples for the serial route.

As a future perspective, it will be interesting to compare the proposed approach with the other methods and carry out experiments for the parallel route and also to study the problem on a large set of benchmark data and real problems.

References

[1] T. Altiok and B. Melamed, *Simulation Modeling and Analysis with Arena*, New York, Elsevier Inc., 2007.

[2] J. Banks, J. S. Carson II, B. L. Nelson, and D. M. Nicol, *Discrete-Event Systems Simulation*, New Jersey, Pearson/Prentice Hall, 2005.

[3] C. Booch, J. Rumbaugh, and I. Jacobson, *The Unified Modeling Language Reference Manual*, New York, Addison-Wesley, 1998.

[4] A. Borshchev and A. Filipov, "From system dynamics and discrete event to practical agent based modeling: reason, techniques, tools, xj technologies," www.xjtek.com and St. Peterburg Technical University.

[5] Ch. G. Cassandras and S. Lafortune, *Discrete Event Systems*, Springer, New York 2008.

[6] J. S. Dagpunar, "Simulation and Monte Carlo," *Wiley*, New York 2007.

[7] J. R. Evans, and D.L. Olsen, *Introduction to Simulation and Risk Analysis*, Upper Saddle River, New Jersey, Prentice-Hall, 1998.

[8] Imagine That, Inc., *Extend User's Manual*, San Jose, California 2006.

[9] W.D. Kelton, R.P. Sadowski, and D.T.Sturrock, "Simulation with Arena," *New York , McGrow-Hill*, 2004.

[10] M. Laguna and J. Marklund, "Business Process. Modeling, Simulation and Design," *New Jersey, Pearson/Prentice Hall*, 2005.

[11] A. M. Law, Simulation Modeling, and Analysis, New Jork, McGraw-Hill, 2007.

[12] U. B. Meyer, S. E. Creux, and A. F. Weber Marin , "Process Oriented Analysis," *Design and Optimization of Industrial Production Systems*, CRC/Taylor&Francis 2007.

[13] M. J. North and Ch. M. Macal, "Managing Business Complexity," *Oxforf University Press*, New York 2007.

[14] J. Recker, *Process Modeling in the 21 st Century*, In: BP Trends, May 2005.

[15] Rockwell Software, Arena Standard User Guide, Rockwell Software, Sewickley, 2005.

[16] E. Yourdon, "Modern Structured Analysis," *New Jersey, Prentice Hall PTR*, 1998.

[17] B. P. Zeigler, H. Praehofer, and T. G. Kim, "Theory of Modeling and Simulation," *N. Y., Academic Press* , 2000.

[18] J. Banks, J. S. Carson, and J. Sy, *Getting Started with GPSS/H*, Wolverine Software, Annandale, Virginia 2003.

[19] CACI Products Company: *SIMSCRIPT III Programming Manual*, San Diego, California 2006.

[20] J. W. Hauge, and K. N. Paige, Learning SIMUL8: *The Complete Guide*, Bellingham, Washington, Plain Vu Publishers, 2004.

[21] J. O. Henriksen, "SLX: The X is for Extensibility", in *Proc. 2000 Winter Simulation Conference*, Orlando, 2000, pp. 183-190.

[22] HyPerformix, Inc., *HyPerformix Workbench Quick Startt Guide*, Austin, Texas 2006.

[23] MicroAnalysis&Design, Inc., *Micro Saint Sharp User's Manual*, Bouder, Colorado 2005.

[24] T. J. Schriber, *An Introduction to Simulation Using GPSS/H*, New York, John Wiley, 1991.

[25] SIMUL8 Corporation, *SIMUL8 User Manual*, Boston, Massachusetts 2005.

[26] X. J Technologies Company, *AnyLogic User's Guide*, Petersburg, Rusia 2005.

[27] J. Banks, Getting Started with AutoMod, Chelmsford Massachusetts, Brooks Automation, Inc 2004.

[28] Delmia Corporation, *QUEST User Manual*, Auburn Hills, Michigan 2005.

[29] Flexsim Software Products, Inc., *Flexsim Simulation Software User Guide*, Orem, Utah 2005.

[30] C. R. Harrell, B. K. Ghosh, and R. O. Bowden, "Simulation Using ProModel," *New York, McGrow-Hill*, 2004.

[31] Lanner Group, Inc., *WITNESS 2006 Tutorial Manual*, Houston, Texas 2006.

[32] PROMODEL Corporation, *ProModel User's Guide*, Orem, Utah 2005.

[33] S. Dynamics, Inc., *Supply Chain Builder User's Manua*l, Maryville, Tennessee 2005.

[34] Jyi-Shane Liu, and K. P. Sycara, "Multiagent Coordination in Tightly coupled Task Scheduling*", Second Int. Conf. on Multi-Agent Systems*, 1996.

[35] J-P. Muller and H. Van Dyke Parunak, "Multi-agent systems and manufacturing," *9th Symposium on Information Control in Manufacturing INCOM* 98.

[36] S. Bussmann, "An agent-oriented architecture for holonic manufacturing control," *First Int. Workshop on Intelligent Manufacturing Systems*, 1998.

[37] P. J. M. Van Laarhoven, E. H. L. Aarts, and J. K. Lanstra, "Job Shop scheduling by Simulated Annealing," *Operations Research*, vol. 40, 1992, pp. 113-125.

[38] J. Heizer and B. Render, Principles of Operations Management, New Jersey, Pearson Prentice Hall, 2008.

[39] J. Ferber, "Multi-Agent Systems: An Introduction to Distributed Artificial Intelligence," *N.Y. ,Addison-Wesley*, 1999.

[40] K. Bremen, "Simulation Supports Production Planning and Scheduling," www. sim-serv.com.

[41] M. Kljajic, I. Bernik, and U. Breskvar, "Production Planning using Simulation and Genetic Algorithms in Multi-Criteria Scheduling Optimization," kibernetika. for. uni-mb.si.

[42] B. Kadar, A. Pfeiffer, and L. Monostoni, "Discrete event simulation for supporting production planning and scheduling decisions in digital factories," www. sztaki.hu.

[43] T. Witkowski, P. Antczak, and A. Antczak, "Application of GRASP procedure for production scheduling and its comparision with other

methods", *Journal of Automation and Information Sciences*, vol. 37, 6(40), pp. 35-40, 2005.

[44] T. Witkowski, P. Antczak, and A. Antczak, "The application of simulated annealing procedure for the flexible job shop scheduling problem", *Proc. 11th International Conferene Information Processing and Management of Uncertainty in Knowledge-Based Systems* (*Industrial Track*), Paris 2006, pp. 21-26.

[45] T. Witkowski, A. Antczak, and P. Antczak, " Planning and Analysis of Production Systems Using Fuzzy Logic," *International Journal of Factory Automation, Robotics, And Soft Computing*, issue 2, pp. 88-95, 2008.

[46] T. Witkowski, P. Antczak, and A. Antczak, „Simulation Modeling and Analysis in Production and Logistics," *International Journal of Factory Automation, Robotics and Soft Computing*, issue 2, pp. 26-34, 2009.

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