

Milan GREGOR^{*}, Juraj HROMADA^{**}, Jozef MATUSZEK^{***}

DIGITAL FACTORY SUPPORTED BY SIMULATION AND METAMODELLING

Abstract

This paper presents the results of research done at the University of Žilina and SLCP Consulting on the area of Digital Factory. The paper focuses on research of support tools e.g. computer simulation and metamodeling in the framework of Digital Factory. The chosen results of research are presented in the paper. The theoretical assumptions and developments were validated on the chosen production systems.

1. INTRODUCTION

Current global markets require high quality, quick production and low costs. These requirements have created the need for collaboration of all professions from engineers and managers to shop floor workers. This co-operation has to be supported by new software systems for designing, testing, process planning, manufacturing and assembling. Such digital framework will allow higher to obtain quality, flexibility, quickness and efficiency.

The utilization of Virtual Reality by the design and optimization of production processes and systems is often entitled as **Digital Factory** [6]. Digital manufacturing enables to realize the process planning simultaneously to product design, shortening time to production and working towards a lean manufacturing practice. All problems of manufacturing processes can be discovered, analyzed and eliminated before any metal is cut in the digital manufacturing environment.

The design of future manufacturing systems is a very complex and complicated task solving estimation of manufacturing system performance, layout planning, integration of other processes, control system, suppliers integration, etc. [6].

Discrete event simulation, supported by 3D animation and virtual reality is used as a very powerful tool for estimation and evaluation of future manufacturing system behavior and performance. Computer simulation enables to test designed manufacturing system by the given, virtual experimental conditions. Simulation, as an experimental method, is time consuming and expensive. Any change of manufacturing systems conditions requires new

* Prof. Ing., PhD. - Department of Industrial Engineering, Faculty of Mechanical Engineering, University of Žilina, Univerzitná 1, 010 26 Žilina, Slovak Republic, milan.gregor@fstroj.uniza.sk

** Ing., PhD. - SLCP Consulting, Univerzitná 6, 010 08 Žilina, Slovak Republic, hromada@slcpconsulting.sk

*** Prof. dr. hab. inż., Bielsko-Biała University, Faculty of Mechanical Engineering and Computer Sciences, Willowa 2, 43-309 Bielsko-Biała, Poland, jmatuszek@ath.bielsko.pl

simulations and evaluations of their results [4]. The simulation is not able to solve automatically all the production problems. It does not offer directly explanation of behavior of the analyzed system and the analyst needs certain experience to be able to interpret the achieved results. The trial and error method is often used in experiments. Even if experiments design and planning increases probability of optimum finding, common current simulation systems do not offer direct single run optimization approach. Optimization systems are complicated, not user friendly and usually very expensive [4].

Modelling of large systems, hierarchical models of the entire enterprises requires high computing power which is multiplied by utilization of 3D animation with virtual reality features. It is difficult to interpret the comprehensive tables with statistical results, even for the experienced analysts. Optimization in this case is only a theoretical desire of the analysts.

Metamodelling offers practical approach to the statistical summarization of simulation results [14]. It enables give to extrapolations in the framework of simulated conditions borders. Metamodels enable to reduce memory requirements by experiments and; on the other side, they can be used as fast support tools for the approximate manufacturing systems control. The decision making process in advanced manufacturing systems often requires quickness.

2. DIGITAL FACTORY

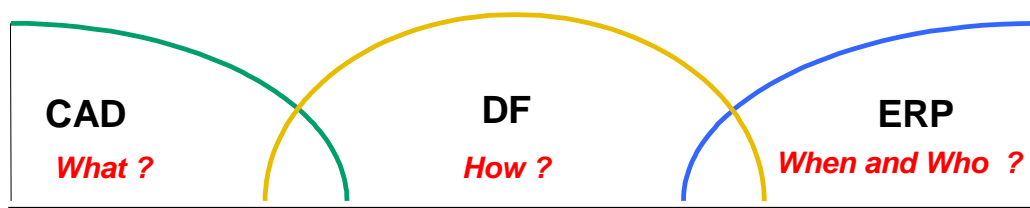


Fig. 1. Integration of Information Systems in Production [3]

The Digital Factory solutions enable visualization and 3D modeling in ergonomics analyses. They offer simultaneously all international standards for ergonomics analyses.

Digital Factory requires the choice of an appropriate shop floor control strategy.

There exist a plenty of production control strategies [7], [8], [9], [10], [12], [13]. Among them, the most known are [5]: Material Requirements Planning (MRP), Load Oriented Control (LOC), Drum Buffer Rope (DBR), Constant Work In Process (CONWIP), KANBAN and Input/Output Control. The following Figure describes the basic principles of CONWIP and DBR production control strategies.

The Digital Factory offers the simulation and virtual reality, in general, as the support tools for the analysis of complex systems. The authors have developed and validated the procedure for the choice of an appropriate shop floor control strategy for a given production system configuration. This procedure was then applied in a decision process by the choice of an appropriate production control strategy in the industry. Furthermore on the authors have used metamodelling to simplify the chosen control of the given production system.

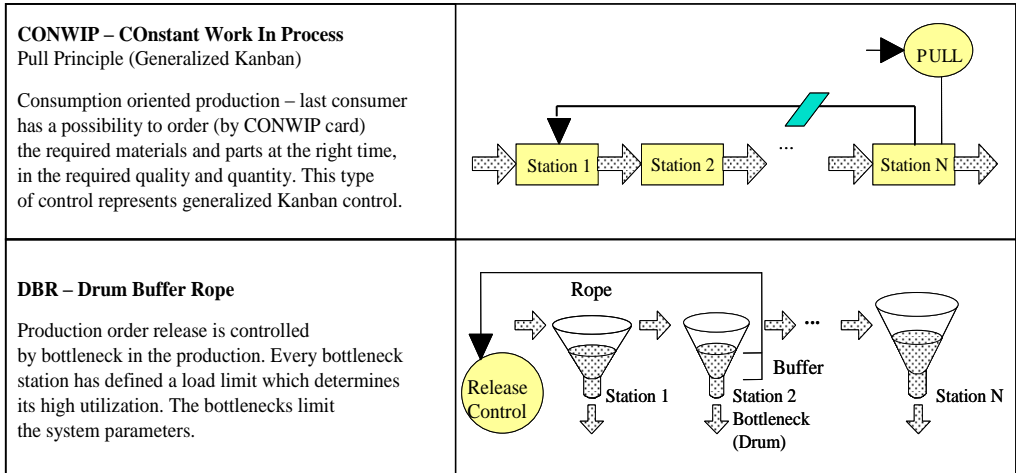
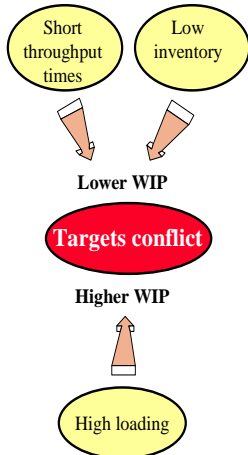


Fig. 2. CONWIP and DBR Production Control Strategies [5]

The production managers can operate production system either by low throughput times and inventories or by high utilization of capacities. Those control strategies are mutually exclusive. The following Figure shows the so called „Production Control Dilemma“.

Production Control Dilemma



Relationship – waiting time versus capacity utilization for M/M/1 system

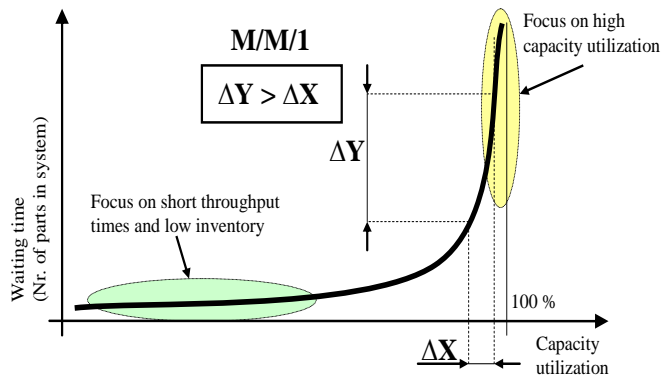


Fig. 3. Production Control Dilemma [5]

3. METAMODELLING

The simulation searches answers to the question: Which results will be achieved by the given combinations of changed input factors? In this case the analysis and definition of input – output relationships takes place. The simulation model represents simplification of real manufacturing system. Even when the real system was simplified by simulation it is still very pretentious and time consuming to conduct all simulation experiments in changed and validated conditions [4]. In search of further simplification possibilities, metamodelling has been developed. The complicated simulation model and experimenting with them are replaced by validated metamodells.

Modelling of large systems such as hierarchical models of the entire enterprises requires high computing power which is multiplied by utilization of 3D animation with virtual reality features. Simulation is a time consuming technique. There exists a possibility to replace very complicated and complex simulation models by validated metamodells and to fasten the decision making process in industry this way. Metamodelling offers practical approach to the statistical summarization of the simulation results. It enables given to extrapolations in the framework of simulated conditions borders and fast approximate manufacturing systems control.

The principle of metamodelling is similar to the hierarchical modelling (see following Figure).

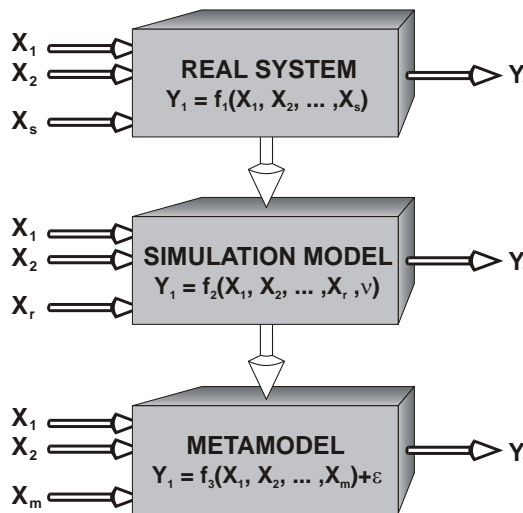


Fig. 4. Metamodeling principles [14]

As it is possible to see from the figure, this approach goes from chaos of reality to organized simulation model followed by modeled input – output relationships of simulation model represented a regressive model.

Metamodel was defined, going out of the description of the real systems behavior whereas the real system was characterized by set of parameters entitled as reactive vector Y_c ($c = 1, 2, \dots, w$). The reactive vector is influenced by real system inputs, so called input factors X_j ($j=1,2,\dots,s$).

The problem of a large parameters number is possible to simplify into system with simple response Y (it is followed only response of one parameter on the given combination of input factors) whereas the system of multiple responses can be evaluated as a set of systems with a simple response.

The relationship between response variable Y and its inputs X_j can be represented as:

$$Y = f_1(X_1, X_2, \dots, X_s). \quad (1)$$

The simulation model is than real systems abstraction whereas an analyst evaluates only a chosen subset of input variables ($X_j / j = 1, 2, \dots, r$), where r is significantly lower the unknown s (we neglect all, from the point of the view of solved problem insignificant input factors).

Simulation response Y' is then defined as a function f_2 of this subset of input variables and random number vector v representing effect of eliminated inputs (allowed failure is the difference between responses of real system and simulation model):

$$Y' = f_2(X_1, X_2, \dots, X_r, v) \quad (2)$$

The metamodel represents further abstraction, in which analyst evaluates only chosen subset of input simulation variables ($X_j / j = 1, 2, \dots, m, m \leq r$) and describes the system as:

$$Y'' = f_3(X_1, X_2, \dots, X_m) + v \quad (3)$$

whereas v represents a given error, with awaited value of zero. Such relationship is possible to describe mathematically by regressive model. The description of input – output relationships of simulation model is then entitled as metamodel.

The obtained regression model goes out from simulation results instead of real data. It means that analyst disposes with more input/output combinations for regression analysis what brings larger span for input variable.

Steps of Metamodel Development

The development of metamodel usually requires steps shown in the following steps:

Problem definition - the Industrial Engineer has to clearly define the problem, its borders and limitations. He has to define the targets and the way the metamodel will be used. The controllable variables have to be known or estimated depending from the fact that the modelled system is real or conceptual. Besides this input variables should be analyzed and required output variables defined.

The framework of input variables definition - often it is difficult to define given input variables ranges and their limitations. It is useful to utilize experts experience and evaluations. The simulation is often used for determination of given ranges of input variables.

The experiments plan design - it is possible to utilize full factorial or partial factorial experiments, depending on relationships among input variables. For example – if the range between the lower and upper value is too wide it is possible to eliminate the effect of extreme values by their replacement with their average values. In this case it is more useful to design and to utilize 3k experiments plan than 2k (the experiments in which three levels of input factors are considered).

Simulation model building - the designed simulation model has to be tested and validated so that it will precisely represent the analyzed problem. Only such model can be used for simulation experiments.

Metamodel development - the metamodels are usually designed in several stages. At first the set of simulation experiments has to be conducted according to factorial experiments design. The factorial experiments plan increases effectiveness of this step. The simulation realized in accordance with the experiments plan brings outputs dependable from input variables and designed model input/output relationships. The simulation results create the bases of data.

As the next stage of regression analysis, typically, it is realized the identification of the most significant input variables. Based on this data, required metamodel is developed, for forecasting of dependent variables.

Metamodel validity testing - this step validates the precise of developed metamodel by the forecasting of dependent variable. One way of validation is the comparison of forecasted outputs from metamodel with the simulation results. The input variables satisfying the model limitations should be used for appropriate metamodel evaluation.

Following Figure shows the proposed procedure for the design and validation of metamodels.

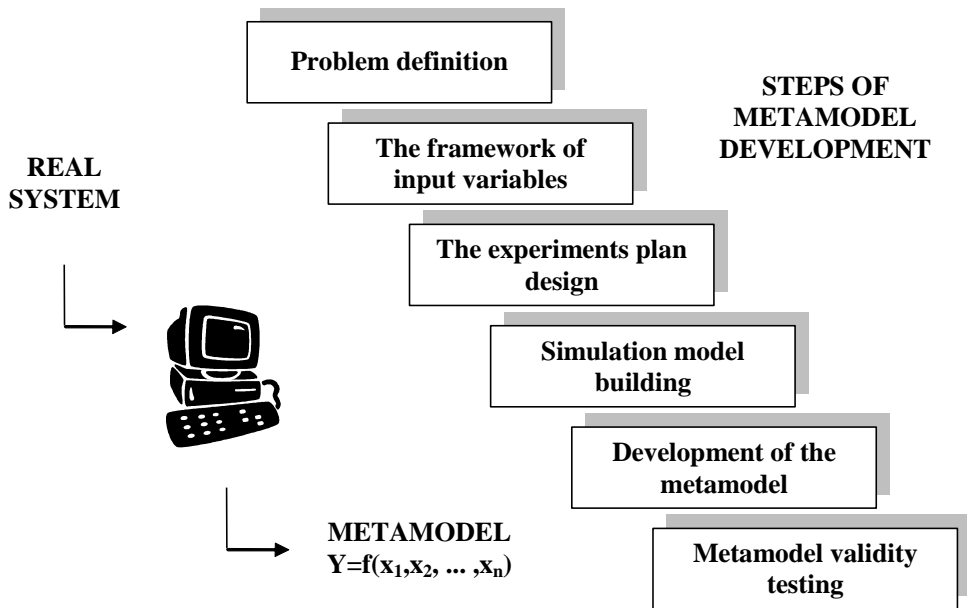


Fig. 5. Steps of Metamodel Development [14]

To be able to achieve a short response in forecasting of manufacturing system behavior under a given control strategy, the below described manufacturing system metamodel has been developed. Simulation has been used for testing the responses of the production system to the proposed changes of chosen control factors. The set of possible control strategies (KANBAN, CONWIP, DBR, LOC and MRP) was tested with the use of the proposed metamodel.

4. SIMULATION MODEL OF PRODUCTION MANAGEMENT

To be able to show the principles of metamodelling we have chosen a simple manufacturing system.

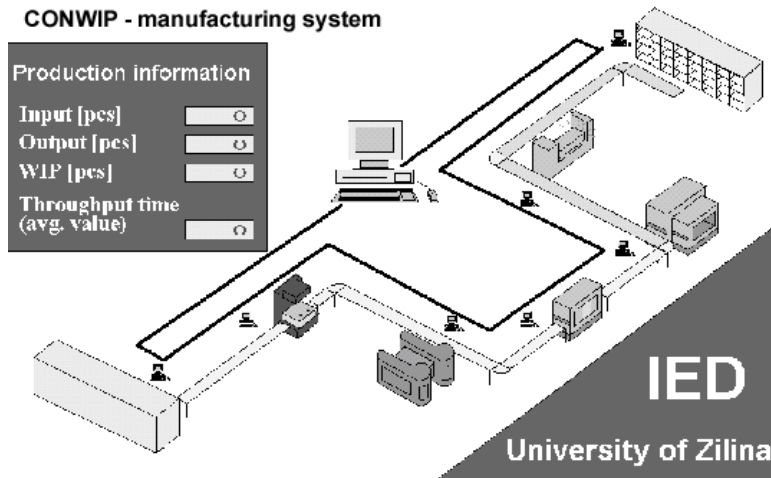


Fig. 6. The Manufacturing System Structure

The simulation model of this manufacturing system has been developed in ARENA simulation system. The metamodel of manufacturing system has been developed, based on simulation results. The different kinds of production control systems (Kanban, Conwip, DBR, LOC and MRP) were tested using this model.

The difference between Kanban and Conwip was that the control circuit in Conwip was built between the first and the last workplace (between the first and the last storage element). It can be used only in the case of production system with the synchronized production line that means production times at each workplace are like the same.

Tab. 1. Summarization of the simulation result

Experiment	E1	E2	E3	E4	E5	E6
No. of Conwip Cards	1	2	3	4	5	8
Avg. Time (min)	61,04	61,27	62,06	64,11	75,87	118,91
WIP (pc)	0,99	1,99	2,99	3,99	4,99	7,99
Production (pc)	16	32	47	60	63	63
Experiment	E7	E8	E9	E10	E11	
No. of Conwip Cards	11	14	17	20	23	
Avg. Time (min)	158,47	197,42	233,13	268,01	299,26	
WIP (pc)	10,99	13,99	16,99	19,99	22,99	
Production (pc)	64	64	64	63	64	

The number of Conwip cards directly determinates the level of work-in-process in the system. In same cases the manufacturing system applies to immediatly change the number of Conwip cards. The managerial staff being responsible for these changes, have to bear in mind, that the number of Conwip cards influences not only work-in-process but also the others output parameters as are production performance, utilization of workplaces, etc. It is not possible easily forecast system response for these changes using standard tools. But there is possibility to simulate these changes in the computer with the various setting of the model parameters and to look how system is responding to them.

We were focusing on the influence of the number of Conwip cards to the defined parameters (production performance, work-in-process, production time) in our analysis. From possible 23 experiments, 11 were chosen for simulation.

Metamodelling is based on looking for the dependence between the input and output parameters with focusing on the mathematical relation of this dependence. For the simplicity we were observing the relation of one factor (number of Conwip cards) with one output parameters (average production time).

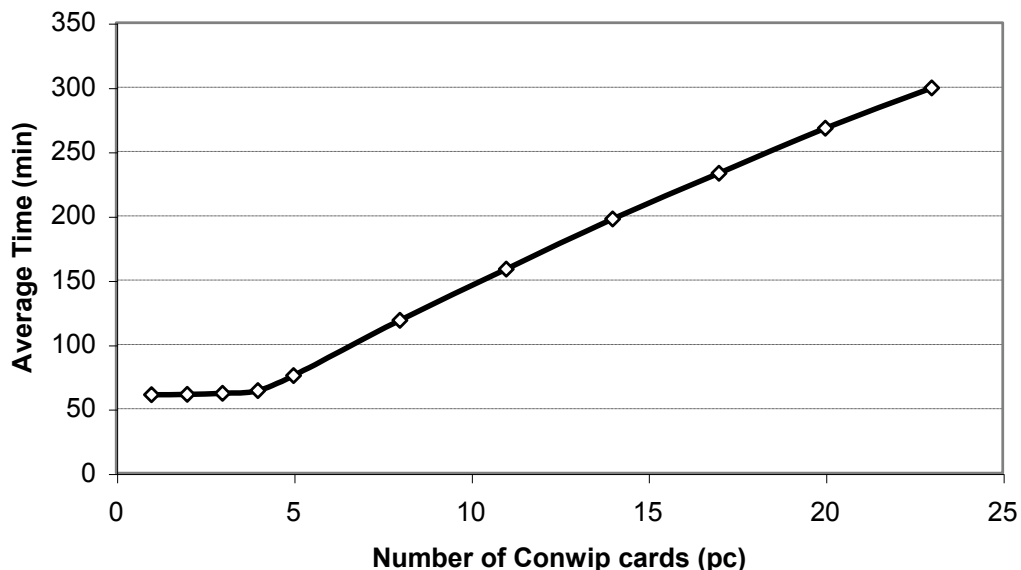


Fig. 7. Relationship Between the Number of CONWIP Cards and Average Throughput Time

The relationships among control factors and production parameters were described by using of regression analysis. The behavior of complex manufacturing system using given control strategy was substituted by its simplified mathematical models (metamodels). The statistical validation (fitting of mathematical model to the simulation output data) was tested by R^2 .

Tab. 2. Results of regress analysis

Type of trend	Trend function	R ²
linear	$y = 11,734x + 30,209$	0,9899
logarithmic	$y = 79,865\ln(x) - 6,099$	0,8097
exponential	$y = 53,637e^{0,0825x}$	0,9642
polynomial II.	$y = 0,0767x^2 + 9,9704x + 35,993$	0,9913
polynomial III.	$y = -0,0277x^3 + 1,0712x^2 + 0,5603x + 54,248$	0,9973
polynomial IV.	$y = 0,0028x^4 - 0,1603x^3 + 3,0816x^2 - 10,028x + 68,259$	0,9994
polynomial V.	$y = -0,0002x^5 + 0,014x^4 - 0,399x^3 + 5,189x^2 - 17,241x + 75,134$	0,9997

R² was calculated as follow:

$$R^2 = 1 - \frac{SSE}{SST}, \quad 0 \leq R^2 \leq 1,$$

$$\text{where: } SSE = \sum (Y_i - \bar{Y}_i)^2 \text{ and } SST = \sum (Y_i^2) - \frac{(\sum Y_i)^2}{n}.$$

Next Figure shows the comparison of several models with the original simulation data. It is evident that the trends with R² close to one give the best results.

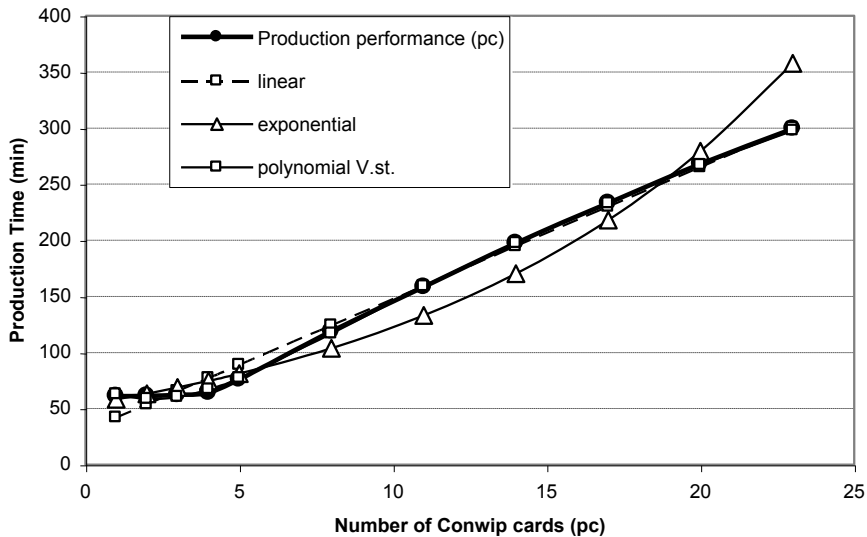


Fig. 8. Comparison of Chosen Models

The developed metamodel offers possibility to find out very quickly and without using simulation the production parameters (e.g. average throughput time, WIP, etc.). The mutual comparison of results from simulation and metamodeling shows insignificant difference (0.0319 min). The part of results of the metamodel validation are shown in the following table. The metamodel is valid on region from one to 22 cards.

Tab. 3. Verification of the metamodel

Comparison of average production time	Number of Conwip cards						
	6	7	10	12	15	19	22
Simulation	89,52	104,62	145,84	173,09	210,14	256,89	290,20
Metamodelling	89,20	102,69	145,28	172,31	209,45	255,71	288,28

The following Figure shows the whole region of metamodel validity. The problem started by using the number of cards over 22. The deviation by 30 cards was significant and so it showed that it was not appropriate to use polynomial equation of the 5-degree as a substitution of simulation data for these values.

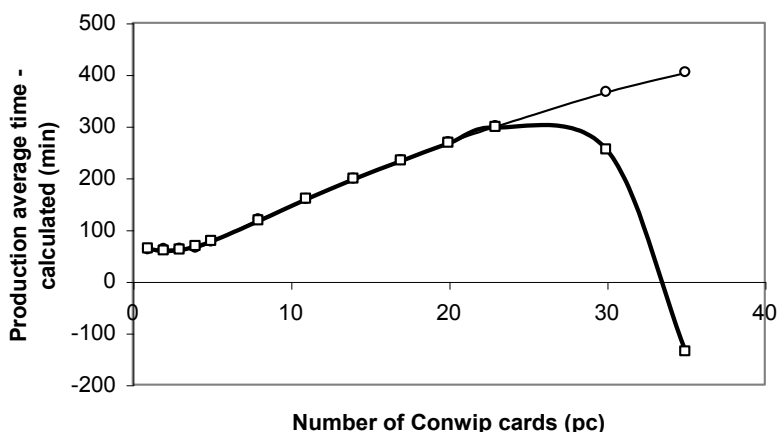


Fig. 9. Progress of the Metamodel Equation Using Polynomial Trend of 5-th Degree

The results of the study showed the possibility to simplify the decision making process by the control of complex production systems in the framework of Digital Factory environment.

Future Research

The future research will be focused on the design of an object set supported by metamodeling which will serve as a support for the design and analysis of pull production systems. The following developed modules will be tested in real full production system.

5. CONCLUSION

Modelling and simulation has become the most important technologies for the future designers of competitive production systems. These technologies have to be further developed, simplified and spread among users. The future designers of production systems will require user friendly solutions with some expert knowledge contained directly inside of the given solutions.

Metamodelling enables simplification of the design and analysis of production systems which, on the other side, supports the improvement of productivity of the designers of production systems and improvement of quality of the designs of new production systems.

This paper was supported by the Agency for Support of Research and Development (APVV), based on agreement No. APVV-0597-07.

References

- [1] FURMANN R., GREGOR M.: *Virtual design – how to be closer to the world class?* Informatyka, Organizacja i Zarzadzanie, ATH Bielsko Biala, 2005, pp. 35-40, ISSN 1644-0315.
- [2] GREGOR M. et al.: *Virtual reality technology as a support for competitiveness and productivity improvement* (in Slovak), University of Zilina. Research project, No.: APVT-20-026304.
- [3] GREGOR M. et al.: *Research of possible utilization of Digital Factory in the Slovak Industry*. University of Zilina, Research project, No.: AV 4/0021/05.
- [4] GREGOR M., KOSTURIAK J., HRDLICZKA V., ACEL P.: *Simulation based comparison of various production control strategies suitable for lean production*. In: Modeling and Simulation. Proceedings of the International Conference. SULOV'93, 1993, pp. 176-183 (in Slovak).
- [5] GREGOR M., KOŠTURIAK J.: *Just-in-Time. Production Philosophy for a Good Management*, ELITA, Bratislava, 1994.
- [6] GREGOR M., MEDVECKY S., MICIETA B., MATUSZEK J., HRCEKOVA A.: *Digital Factory*, SLCP Zilina, 148 pp., KRUPA print 2007, ISBN 80-969391-5-7.
- [7] GSTETTNER S., KUHN H.: *Analysis od Production Control Systems Kanban and CONWIP*. International Journal of Production Research, 1996, Vol.34, No.11, pp.3253-3273.
- [8] HUANG P. Y., REES L. P., TAYLOR III B. W.: *A simulation analysis of Japanese just - in time technique (with Kanbans) for a multiline, multistage production system*. Decision Sciences, 1983, 14(3), 326-344.
- [9] KOŠTURIAK J., GREGOR M.: *Simulation von Produktionssystemen*. Springer Verlag, Wien, 1995.
- [10] LEE L. C.: *Parametric appraisal of JIT system*. International Journal of Production Research, 1987, 25(10), 1415-1429.
- [11] MICIETA B. et al: *Virtual Reality in sophisticated assembly processes* (in Slovak), University of Zilina, Research project, No.: AV 1014/2003.

- [12] PHILIPOOM P. R., REES L. P., TAYLOR III B. W., HUANG P. Y.: *An investigation of the factors influencing the number of Kanbans required in the implementation of the JIT technique with Kanbans*. International Journal of Production Research, 1987, 25(3), 457-472.
- [13] SPERMAN M. L., WOODRUFF D. L., HOPP W.J.: *CONWIP: Pull alternative to Kanban*. International Journal of Production Research, 1990, 28, 879-894.
- [14] STEFANIK A., GREGOR M.: *Rapid development of the new production system with the support of computer simulation*, Rapid technologies, Wroclaw, CAMT, October 2004, pp.234-242.