Lean Manufacturing Systems Optimisation Supported by Metamodelling

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Abstract. This paper presents metamodelling method as a practical approach to the statistical summarisation of simulation results. Metamodels enable to reduce memory requirements by experiments and, on the other side, they can be use as fast support tools for the manufacturing systems control. The chosen metamodelling approach was applied in various projects. Given example shows practically how can be metamodel developed and verified using simple Conwip production systems.

1 Introduction

The current and future markets require production systems with high flexibility, effectiveness and reliability. To achieve such targets the designers and planners of production systems have to utilize advanced technologies, like modelling, simulation, digital factory, etc.

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

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 behaviour and performance. Simulation enables to test designed manufacturing system by given, virtual experimental conditions.

Current top simulation systems are very expensive for developing countries, what slow downs the spread of this very powerful method in their industries.

Simulation, as the experimental method, is time consuming and expensive. Any change of manufacturing systems conditions requires new simulations and evaluations of their results.

The simulation is not able to solve automatically all production problems. It does not offer directly explanation of behaviour of the analysed system and the analyst

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needs certain experience to be able to interpret achieved results. The trail and error method is often used by experiments. Even if experiments design and planning increases probability of optimum finding, common current simulation systems don´t offer direct single run optimisation approach. Optimisation systems are complicated, not user friendly and usually very expensive.

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

Metamodelling offers practical approach to the statistical summarisation of simulation results. It enables a given extrapolations in the framework of simulated conditions borders. Metamodells 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 fastens is often required by decision making process in advanced manufacturing systems.

2 Metamodel

The simulation searches answers to the question: Which results will be achieved by a given combinations of changed input factors? In this case goes on the analysis and definition of input – output relationships. 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 by changed and validated conditions. In search of further simplification possibilities, metamodelling was developed. The complicated simulation model and experimenting with them are replaced by validated metamodels. This was enabled by the approach which is very similar to hierarchical modelling (see following figure).

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

Kleijnen (1979a) defined metamodell, going out of description of real system behaviour whereas real system was characterised by set of parameters entitled as reactive vector Yc (c = 1,2, ..., w). The reactive vector is influenced by real system inputs, so called input factors Xj (j=1,2,....,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.

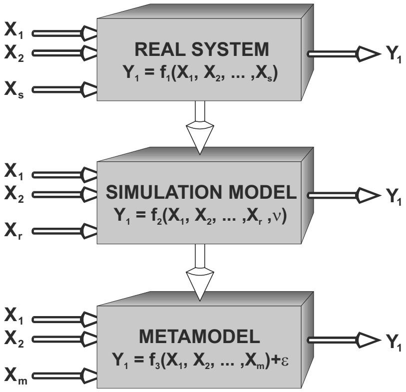

Fig.1. Metamodelling principles

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

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

The simulation model is then real system abstraction whereas analyst evaluates only chosen subset of input variables (X_j /j = 1, 2, ..., r) , where r is significantly lower as unknown s (we neglect all, from the point of view of solved problem unsignificant input factors).

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

$$Y' = f_2(X_1 , X_2 , ..., X_r , \nu) \qquad (2)$$

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

$$Y'' = f_3(X_1 , X_2 , ..., X_m) \underset{\cdot}{+} \varepsilon \qquad (3)$$

whereas ε 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.

3 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 analysed 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 usefull 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).

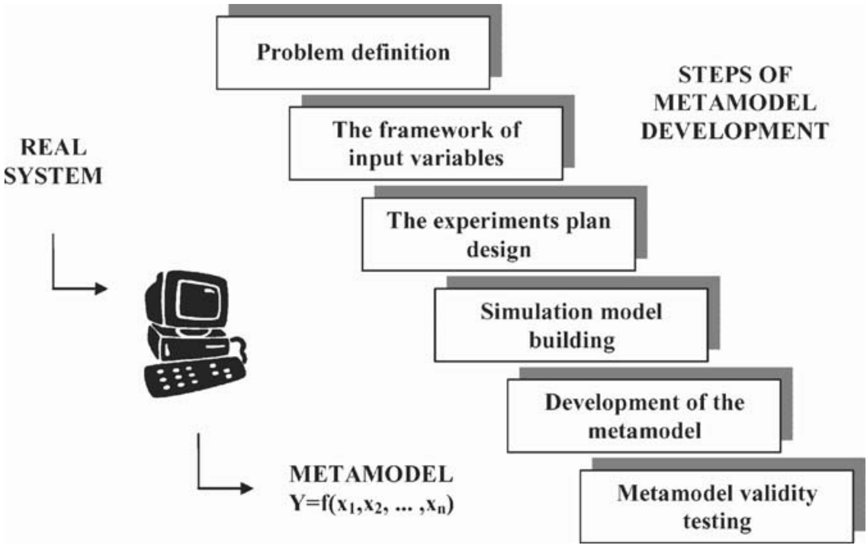

Fig. 2. Steps of metamodel development

Simulation model building - the designed simulation model has to be tested and validated so that it will precisely represent the analysed 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 realised 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 realised 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.

4 Simulation Model of Production Management

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

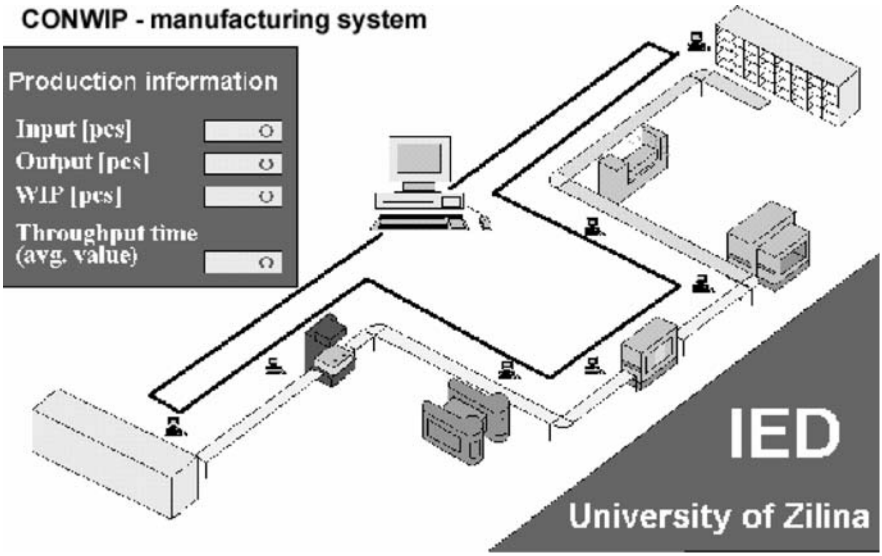

Fig. 3. The Manufacturing System Structure

The simulation model of this manufacturing system was developed in the software ARENA. The metamodel of manufactuirng system was developed, based on simulation results. Using this model we were testing different kind of production systems (Kanban, Conwip, DBR, LOC and MRP).

The difference between Kanban and Conwip was, that the control circuit in Conwip is built between the first and the last workplace, let us say between the first and the last storage. 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.

The number of Conwip cards directly determinates the level of work-in-process in the system. In same cases the manufacturing system applies to immediately 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.

Table 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	

In our analysis we were focusing on the influence of the number of Conwip cards to the defined parameters (production performance, work-in-process, production time). From possible 23 experiments we chose 11 being simulated.

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).

Using regress analysis we tried to describe this relation. We tried to substitute achieved behavior with the mathematical function using different types of trends.

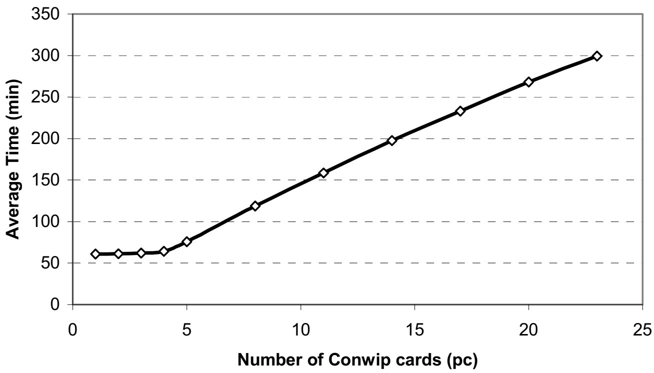

Fig. 4. Relation between the number of Conwip cards and average production time

R^2 reflects error rate being creating by the substitution of obtain value with the value from the trend equation. R^2 was calculated as follow:

$$R^2 = 1 - \frac{SSE}{SST}, \qquad 0 \le R^2 \le 1,$$

where $SSE = \sum (Y_i - \overline{Y_i})^2$ and $SST = \sum (Y_i^2) - \frac{(\sum Y_i)^2}{n}$.

Next figure shows comparison of several trends and the origin value. It is clear that the trends with $R^2 \rightarrow 1$ give better results.

Table 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	$y = 53{,}637e^{0{,}0825\cdot x}$	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

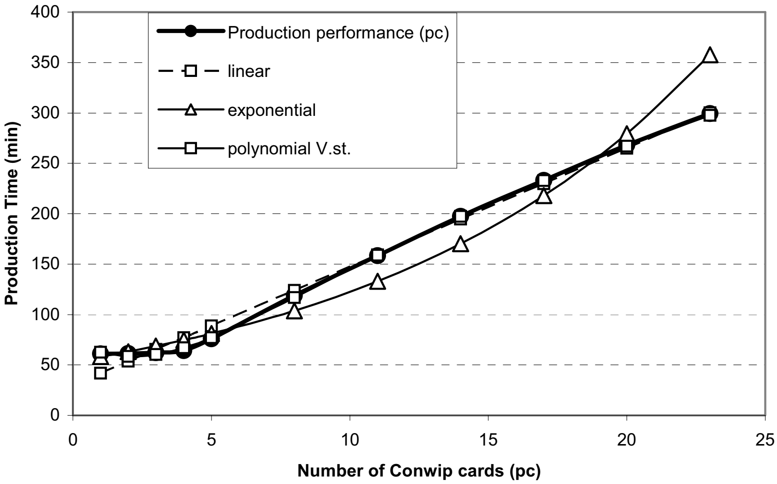

Fig. 5. Comparison of chosen trends course

Predefined equation gives possibility to very quickly and without using simulation find out average production time for given number of Conwip cards. For example assuming the number of Conwip cards to 14, based on polynomial equation of the 5-th degree, we can calculate the average production time to 197.4519 min. Comparison calculating value with the simulation result shows insignificant difference (0.0319min). We made comparison of the control value (being not used by developing metamodel) to verify the quality of metamodel. The results of the verification are in the following table:

Table 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 problem started by using value over the interval being used by development of metamodel. If we assumed using of 30 Conwip cards, the average time from calculation is 254.3195 min and from simulation is 365.63 min. This difference is really important and as it is shown in the next figure. It is not appropriate to used polynomial equation of the 5-degree as a substitution of simulation for these values.

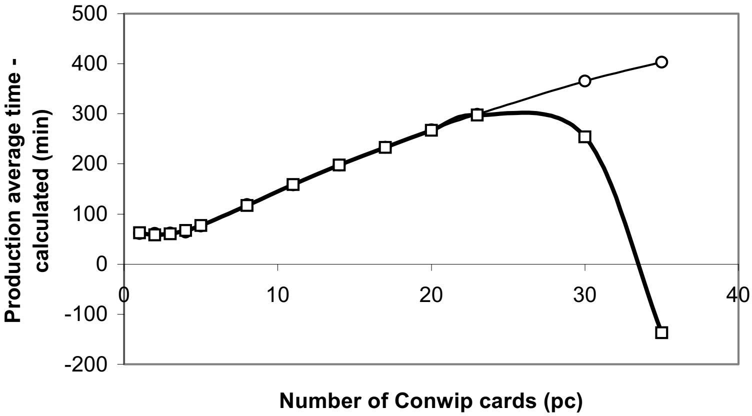

Fig. 6. Course of the metamodel equation using polynomial trend of 5-th degree

5 Conclusion

In the paper we show development of simple metamodels, it means input-output relation with only one input factor. Of course, there is possibility to enlarge this approach to developing metamodel of two input parameters (for examples number of Conwip cards and various types of the bottleneck solution) and one output parameter (for example average production time). The main advantages of the metamodels are simply and fast forecasting behaviour of the systems with given condition (it is not necessary to change the model at first) and easy and simplicity of their using. The main disadvantage is the sophistication of metamodel development.

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