POLITECHNIKA LUBELSKA

Optimization of Production Processes

editors

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*RADOSŁAW CECHOWICZ**

1. Scheduling in a single-machine manufacturing system with resource constraints

Introduction

In a single machine production environment with a storage and transport system, indivisible tasks were delivered on palletes to the machine. One palette could hold up to four tasks (Fig.1.1). The tasks from the palette can be processed in any order.

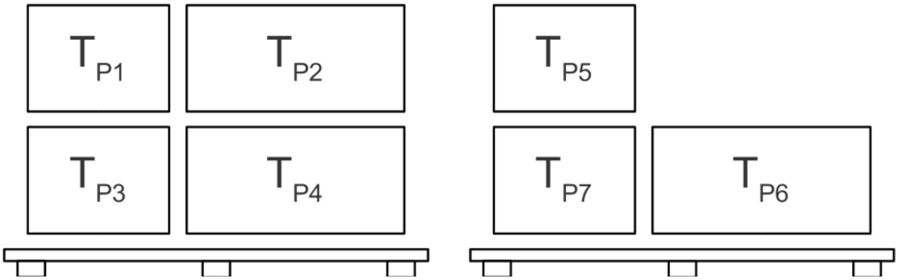

Fig. 1.1. A manufacturing order consisting of 7 tasks packed on two palettes

Tasks were defined by the processing time (designated as $T_{P1}..T_{P7}$ in Fig.1.1 and Fig. 1.2) and the auxiliary time ($T_{A1}..T_{A5}$ in Fig. 1.2) representing all the activities associated with the processing (setting up, loading, etc.). Both times could be defined individually for each task. The palette could be moved away and replaced with a new one only after all the tasks assigned to it had been completed. The time required for replacing the palette (transportation time) is marked as T_T in Fig.1.2. Palette replacement time was assumed to be equal for all palettes.

The machine was available periodically for a limited time T_M. For example, the machine could be available for 8 hours a day. At the end of each availability period, the machine had to be maintained, which was marked as T_S in Fig. 1.2. The machine could be stopped only after processing of a task had finished. The machine maintenance and the palette replacement were independent of each other and could be performed at the same time. As the tasks were indivisible, it was not permitted to start a task that could not be completed within the machine availability time.

The complete order (all tasks) was assumed to be known at the start of scheduling, although plan updates were possible at any time. The objective of scheduling was to minimize the cost function, which, in the simplest case, could be defined as the time to complete all tasks C_{max}. In the other version of the same problem, not considered here, the objective of scheduling was to minimize

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the total machine idle (waste) time ΣT_S within a given period (for example, within 5 working days). All tasks were assumed to have the same priority and deadline.

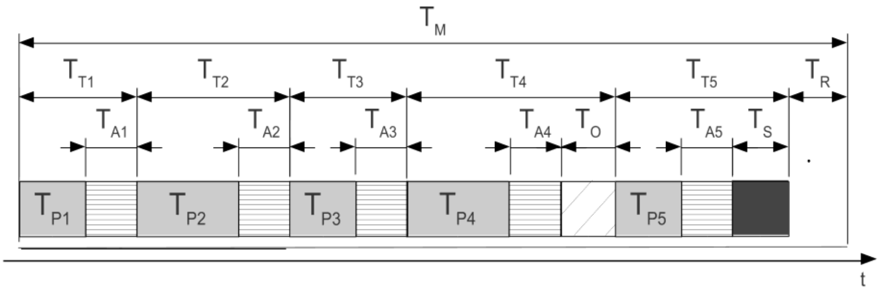

Fig. **1.2. Work plan for one machine availability period T_m**

Example plan for one machine availability period is shown in Fig.1.2. The symbols used are:

- T_M – the period of machine availability,
- T_{P1}... T_{P5} – task processing times,
- T_{A1}... T_{A5} – auxiliary time related to tasks,
- T_O – palette replacement time,
- T_S – machine maintenance time,
- T_{T1}... T_{T5} – total processing time of a task,
- T_R – machine idle time (unused machine availability time).

The total processing time T_{Ti} was introduced to facilitate testing the scheduling algorithm with the standard data. T_{Ti} represented the total time associated with the task, including palette replacement and machine maintenance where applicable.

The scheduling problem here was similar to the one-dimensional problem of bin packing, where the objective was to find minimum number of boxes (usually equal in size) that could accommodate a number of pre-defined items. In the one-dimensional problem, the boxes and items were defined by a single number (the length). Here, the box size could be related to the machine availability time T_M, and the items to the total processing time of a task T_{Ti}. The problem of bin packing is NP-hard, which was proven for example by (Cook 1971) and (Karp 1972). In the bin packing problem, it was possible to estimate the minimal number of boxes if we assumed that the items were divisible and the capacity of boxes could be used up to 100%. Then, it would be enough to divide the total length of all items by the capacity of the box.

The minimum machine time L_{min} required for processing an order containing N tasks can be calculated from the formula:

$$L_{min} = \Sigma T_{Ti} \tag{1.1}$$

The minimal number of machine availability periods (shifts) T_M required for processing the order M_{min} can be calculated from the equation (assuming that tasks are divisible and all periods of availability T_m have the same length):

$$M_{min}=ceil(L_{min}/T_M) \quad (1.2)$$

This is, however, only a rough estimate of a minimal solution in a real manufacturing environment, where all the resource constraints apply. The real minimum solution P_{min} depends on the length of the machine availability period T_M and how it relates to the distribution of processing times T_{Ti}.

A variety of heuristic bin-packing strategies is documented in the literature. Their advantage is the ability to achieve a good plan in a relatively short time, especially for certain sets of data. For example, the "First-Fit" (FF) and "Best-Fit" (BF) allow to obtain a solution in an intuitive way by just packing items one by one to the first box where they fit (according to a certain criteria). It was proved by (D. S. Johnson et al. 1974) that the worst case solution for the FF strategy is $C_{max}=1.7P_{min}+2$ (or $C_{max}=1.7P_{min}+0.7$ according to (Xia & Tan 2010)). To further improve the result, the items could be sorted in order of decreasing processing time T_{Ti} before packing (the First-Fit-Decreasing, FFD). The FFD algorithm, in the worst case, produces a solution $C_{max}=11/9P_{min}+1$ (Yue 1991). In fact, the actual performance of these algorithms is often better than these estimates. Heuristic strategies can be used to estimate the maximum number of boxes needed to pack all items, and to provide a reference point for the evaluation of the quality of packing algorithms. The heuristic algorithms like proposed by (Fleszar & Charalambous 2011) and (Fleszar & Hindi 2002) could also be used directly in well defined manufacturing environments. Some other strategies are described by (Coffman,Jr. et al. 1997), (Csirik et al. 1999) or (Schwerin & Wäscher 1997).

Another way to search for the solution of the bin-packing problem is to use the artificial intelligence algorithms (AI). AI algorithms can search the entire space of solutions (e.g. genetic algorithms) or only a selected branch (e.g. annealing). Contrary to the heuristic approaches, AI can produce good solutions regardless of the input data. Random nature of the search helps to avoid the pitfalls associated with a specific distribution of the size of elements. The performance analysis of genetic algorithms applied to the problem of bin-packing was presented by (Falkenauer 1996) and others.

1.1. The scheduler

A modified genetic algorithm was developed to facilitate scheduling. The algorithm respected the limitations of the palette transport system and other constraints of the production environment. The scheduling algorithm was programmed in Java, using the JGAP library (Meffert & Rotstan 2010). The tasks were represented by integer genes that contained unique job numbers. The sequence of genes in the chromosome represented the schedule (solution). The only operation allowed on the chromosome was a permutation of genes. The mutation operator could perform two operations:

1. changing the order of entire palettes - swapping two randomly selected palettes,
2. changing the order of tasks on a palette (rolling the tasks).

Both operations (a and b) were performed at random. The number of swapping operations performed during a single mutation could be controlled by the parameter K (integer).

In the real manufacturing system, the fitness function did take into account factors like priorities and deadlines as well as the cost of the retrieval of palettes from the warehouse. However, in the further part of the article, these limitations were removed to make the results comparable to the published cases.

The cost of the plan could be limited by synchronising palette replacements with the machine maintenance at the end of each availability period. Therefore, including the time waste ΣT_R into the fitness function was not a good idea as this promoted solutions with a large number of unsynchronised transport and maintenance actions.

1.2. Assessment of results

For the manufacturing data, the algorithm allowed to obtain $C_{max}<1.04L_{min}$ which was about 10% better than the average manual scheduling result. The algorithm was also tested with publicly available data - OR-library (Beasley 2010, Beasley 1990 and the project BINPP (Scholl & Klein 2011) to compare the performance with other solutions. The results are summarized in Table 1. In all tests, the input data were assumed to be total processing times (T_T) and each palette contained only one task (to break dependencies between tasks). The obtained results were in general similar to those described in the publications. In some cases, e.g. for difficult cases from (Scholl & Klein 2011) the results were worse.

Columns in Table 1.1: *Name* - name of data file, *No. of tasks* - the number of tasks in the order, M_{min} - theoretical minimal solution calculated using the formula (1.2), *Alg. orig.* - the best solution obtained by the authors of the source project, *Alg. test* - the best solution obtained in the scheduling system.

Tab. 1.1 Scheduling results for sample data from published projects

No.	*Name*	*No. of tasks*	M_{min}	*Alg. original*	*Alg. test*
1	u120_00[a]	120	48	48[a]	50
2	u120_19[a]	120	49	50[a]	50
3	hard0[b,c]	200	55	56[b,c]	58
4	hard28[b,d]	160	61	62[b,d]	62

a) (Beasley 2010), b) (Scholl & Klein 2011). c) (Wróblewski 2005),d) (Belov & Scheithauer 2003)

The scheduling process log for the best result obtained for the u120_19 data set is presented in Fig. 1.3. The solid line represents the quality of the solution (*Fitness*=C_{max}) which corresponded directly to the number of boxes used (shown on the right side). The size of the population in this case was 25. The computation time was about 12s for each 1000 generations (AMD Athlon 64 X2 4200+, 2GB RAM). The computations were stopped after there was no better plan found during 3000 generations.

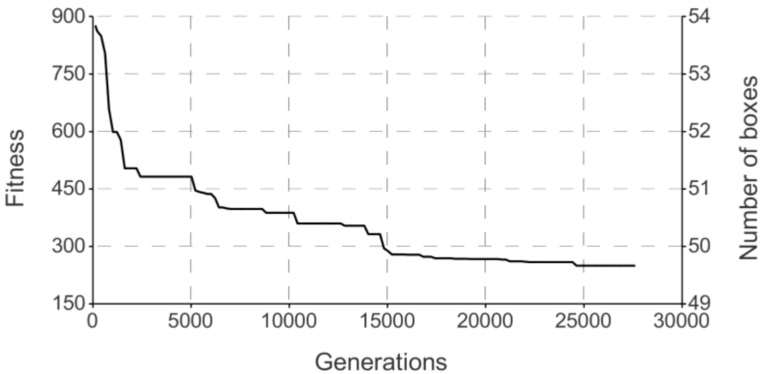

Fig. 1.3 A process of scheduling of the u120_19 data set from Table 1 (Box capacity=150, K=5)

A series of tests was made to check how the distribution of the scheduling results depended on the size of gene population. There were 450 tests performed, 50 for each population size from 5 to 45, as shown in Fig. 1.4. The u120_19 data set was used as input. The number of gene swaps during one mutation, marked as the parameter *K*, was constant during all the tests. The lowest C_{max} was obtained for population sizes 25 and 40, however, the computation time was much longer in the latter case.

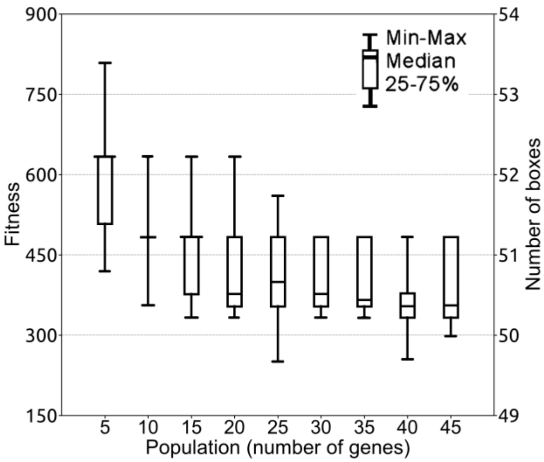

Fig. 1.4. The distribution of results as a function of gene population for the u120_19 data set from Table 1 (Box capacity=150, K=5)

The mutation operator could be tuned up with the parameter *K*, which allowed to control the number of actual gene swaps during one mutation. In a typical genetic algorithm, the number of swaps is usually one (*K=1*). It was noted during the tests that increasing the number of gene switching operations could improve the quality of generated solutions and reduce computation time.

Fig. 1.5 shows the results of scheduling ($Fitness=C_{max}$) for the data set from the manufacturing environment. A total of 500 tests were performed, 50 for each *K* from 1 to 10. The graphs show the range of obtained solutions, and the median for each of the series (*K=const.*). It could be noted that for *K=5..9* the median is in the bottom of the box-plot, which means that 50% of all results obtained in these series is in the lower range of values. The probability of obtaining a good result (from the bottom part of the chart) is higher for *K=5..9* than for other *K*. The minimum solution is the same for all *K* (Fig. 1.5).

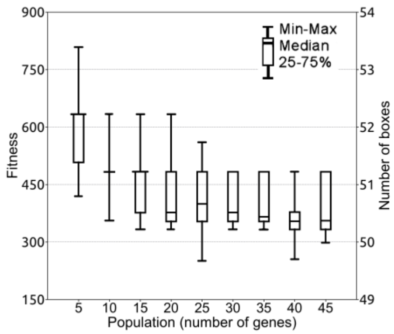

Fig. 1.5. Distribution of scheduling results for data from manufacturing system

On the other hand, the number of generations needed to produce a result grows as K is increasing (Fig. 1.6).

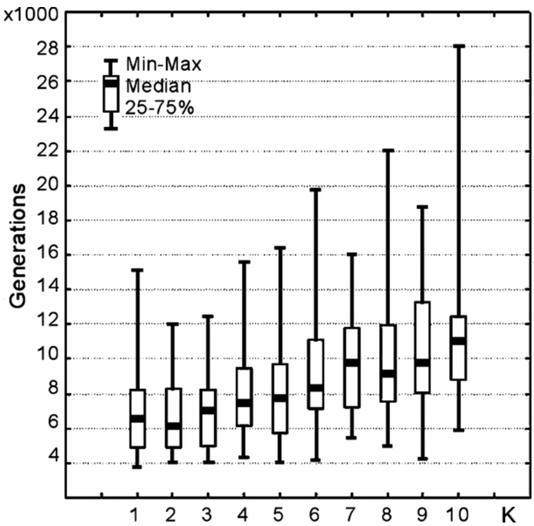

Fig. 1.6. Number of generations needed to get a solution for tests from Fig. 1.5

Histograms for C_{max} for the selected K are presented in Fig. 1.7. The results of the non-parametric median test ($\chi^2=19$, $df=9$, $p=0.0254<0.05$, $\alpha=0.05$) proved that the distribution of the values of the variable C_{max} in the considered groups differed significantly at the arbitrarily adopted level of significance. Hence the conclusion that the quality of scheduling depended on the value of the parameter K. This was probably related to the fact that the scheduling problem was not linear and the minimum solution could not usually be reached incrementally by finding better and better plans. To obtain a better solution, more than just one gene swap had to be made, which might lead to temporal worsening of the plan (increased C_{max}). The ability of the algorithm to overcome local minima and to broaden the search area around the current solution could be increased by augmenting K. The fact that the distribution of C_{max} depended on K, might also come from the fact, that there was no cross-over operator, which would allow the exchange of information between chromosomes and thus widening of the search area.

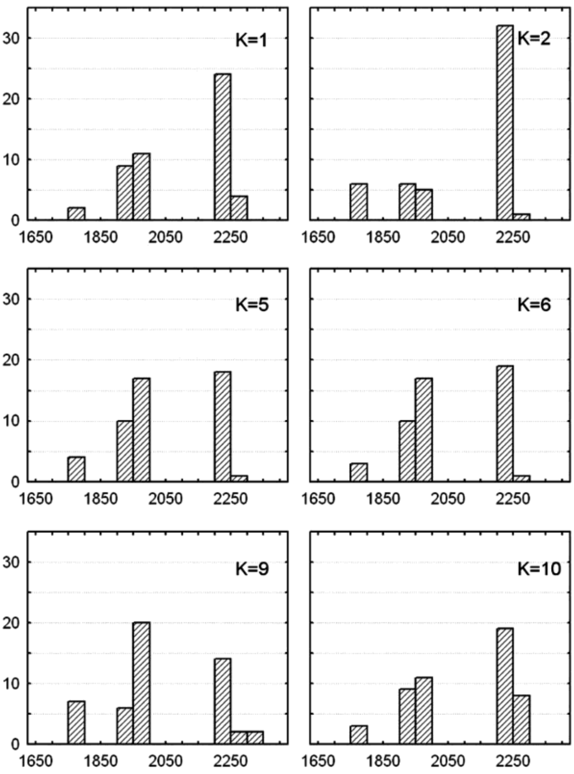

Fig. 1.7. Distribution of obtained results C_{max} for selected K

By properly adjusting the value of *K*, the time needed to find a solution could be decreased. Assuming that the tests were random, the expected number of tests (*I*) to get the solution $C_{max}<2050$ would be *I=9* for *K=1*, *I=12* for *K=2*, *I=6* for *K=5* and *I=5* for *K=9*. Expected computation time can be obtained by multiplying *I* by the average computation time for each group. It would turn out then that the expected time to get the solution $C_{max}<2050$ would be the shortest for *K=5* (48,400 generations) and the longest for *K=2* (80,800 generations). For *K=1*, the expected computation time would be 63,400 generations.

Conclusions

The application was designed for a manufacturing system working on a weekly cycle (schedule). The scheduling of a typical weekly order (about 200 tasks) could be done in a few minutes. As the transport and technology constraints were taken into account, the plans generated by the system were feasible. Machine availability periods could be defined individually, as well as the parameters (execution time, auxiliary time). In the target environment, the application allowed to significantly reduce the non-productive time. The computation time could be reduced by adjusting the parameter *K*, representing the number of gene swaps during a single mutation operation. Tests conducted on the publicly available data from similar projects have shown that the algorithm produced quality solutions comparable with those described in the literature.

The omission of the cross-over operator seemed to be justified by the simplicity and speed of the algorithm. However, no research was done to check how the operator would contribute to the final performance. The chosen chromosome structure did not allow for easy integration of the cross-over operator. (Falkenauer 1996) observes that the use of the cross-over operator could speed up the first phase of genetic search where the solution candidates are not known yet. The search for the initial solution candidates should be more complete if the cross-over operator was used, therefore the future research will focus on this issue.

References

[1] Beasley, J.E., 2010. *OR-Library*, Available at: http://people.brunel.ac.uk/~mastjjb/jeb/orlib/.

[2] Beasley, J.E., 1990. OR-Library: Distributing Test Problems by Electronic Mail. *Journal of the Operational Research Society*, 41, pp.1069-1072.

[3] Belov, G. & Scheithauer, G., 2003. A Branch-and-Cut-and-Price Algorithm for One- and Two-Dimensional Two-Staged Cutting (Stock) Problems. Av. at: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.12.7832.

[4] Coffman, Jr., E.G., Garey, M.R. & Johnson, D. S., 1997. Approximation algorithms for bin packing: a survey. In Boston, MA, USA: PWS Publishing Co., pp. 46–93. Av. at: http://dl.acm.org/citation.cfm?id=241938.241940.

[5] Cook, S.A., 1971. The complexity of theorem-proving procedures. In ACM Press, pp. 151-158. Available at: http://dl.acm.org/exportformats.cfm?id=805047&expformat=bibtex [Accessed September 5, 2011].

[6] Csirik, J. et al., 1999. A Self Organizing Bin Packing Heuristic. In *ALENEX'99*. pp. 246-265.

[7] Falkenauer, E., 1996. A hybrid grouping genetic algorithm for bin packing. *JOURNAL OF HEURISTICS*, 2, p.5-30.

[8] Fleszar, K. & Charalambous, C., 2011. Average-weight-controlled bin-oriented heuristics for the one-dimensional bin-packing problem. *European Journal of Operational Research*, 210(2), pp.176-184.

[9] Fleszar, K. & Hindi, K.S., 2002. New heuristics for one-dimensional bin-packing. *Computers & Operations Research*, 29(7), pp.821-839.

[10] Johnson, D. S. et al., 1974. Worst-Case Performance Bounds for Simple One-Dimensional Packing Algorithms. *SIAM Journal on Computing*, 3, p.299.

[11] Karp, R.M., 1972. Complexity of Computer Computations. In *[http://www.cs.berkeley.edu/~luca/cs172/karp.pdf Reducibility Among Combinatorial Problems]*. New York: Plenum, pp. pp.85-103.

[12] Meffert, K. & Rotstan, N., 2010. *Java Genetic Algorithm Package*,

Available at: http://jgap.sourceforge.net/.
[13] Scholl, A. & Klein, R., 2011. *Bin Packing*, Av. at: http://www.wiwi.uni-jena.de/Entscheidung/binpp/.
[14] Schwerin, P. & Wäscher, G., 1997. The Bin Packing Problem: A Problem Generator and Some Numerical Experiments with FFD Packing and MTP. *International Transactions in Operational Research*, 4(5,6), pp.377-389.
[15] Wróblewski, J., 2005. *Problem pakowania (Bin packing)*, Available at: http://www.jakubw.pl/sci/binpack/index.html.
[16] Xia, B. & Tan, Z., 2010. Tighter bounds of the First Fit algorithm for the bin-packing problem. *Discrete Applied Mathematics*, 158, pp.1668-1675.
[17] Yue, M., 1991. A simple proof of the inequality FFD (L) $\leq$ 11/9 OPT (L) + 1, $\forall$L for the FFD bin-packing algorithm. *Acta Mathematicae Applicatae Sinica*, 7, pp.321-331.

SCHEDULING IN A SINGLE-MACHINE MANUFACTURING SYSTEM WITH RESOURCE CONSTRAINTS

Abstract: A system for scheduling indivisible tasks on a single, periodically accessible machine was presented. Due to the constraints existing in the environment, the scheduling problem was similar to the one-dimensional bin-packing. The tasks were grouped and transported on palettes. A modified genetic algorithm, without a cross-over operator was proposed for scheduling. The mutation operator could be tuned with the parameter *K* representing the number of gene changeovers. The scheduling algorithm could be tuned for speed and quality by adjusting the parameter. The observation was proved statistically by means of the median test run for the set of 500 results.

Key words: scheduling algorithms, bin-packing, genetic algorithm, single machine, resource constraints, manufacturing control

SZEREGOWANIE ZLECEŃ PRODUKCYJNYCH NA JEDNĄ MASZYNĘ Z OGRANICZENIAMI ZASOBÓW

Streszczenie: W artykule zaprezentowano eksperymentalny system szeregowania niepodzielnych zleceń produkcyjnych na pojedynczej maszynie z ograniczonym czasem dostępności. Opisany problem szeregowania jest podobny do opisywanego w literaturze jednowymiarowego pakowania plecaka. Zadania produkcyjne były dostarczane do maszyny w formie pakietów (palet) zawierających od jednego do czterech zleceń. Do szeregowania zleceń zaproponowano zmodyfikowany algorytm genetyczny, wykorzystujący mechanizm mutacji do zmiany kolejności zleceń w planie produkcji. Sposób działania algorytmu można było kontrolować poprzez zmianę wartości parametru *K*, określającego odsetek mutacji w każdym pokoleniu. Wykazano, że dla rozpatrywanych przypadków, zmieniając wartość parametru można było wpływać na szybkość działania algorytmu genetycznego oraz na jakość uzyskiwanych rozwiązań. Obserwacja ta została potwierdzona przez test statystyczny przeprowadzony na próbie 500 wyników szeregowania przykładowego zbioru zleceń produkcyjnych.

Słowa kluczowe: algorytmy szeregowania, zagadnienie plecakowe, algorytm genetyczny, pojedyncza maszyna, ograniczenia zasobów, sterowanie produkcją

*GRZEGORZ KŁOSOWSKI**

2. Enhancing the optimization capabilities of simulation software with OPTQUEST for arena rockwell

Introduction

On the market there are many ready-made software products for modeling and simulation processes in different areas of life (Tab.2.1). One of the most popular simulation software that is dedicated to wide area of business aspects is Arena Rockwell. According to Rockwell Automation, the vendor of the software, typical applications of Arena consist of e.g. DES software tool purposes and any process that can be described [5]. The software is applied for such primary markets as: manufacturing, 6-sigma, packaging, supply chain, airports, healthcare, military and defense, service, call centers, mining, ports etc. [11].

Tab. 1.1. Optimization for Simulation: Commercial Software Packages [3]

Optimization Package (Simulation Platform)	Vendor (URL)	Primary Search Strategies
AutoStat (AutoMod)	AutoSimulations, Inc. (www.autosim.com)	evolutionary, genetic algorithms
OptQuest (Arena, Crystal Ball, et al.)	Optimization Technologies, Inc. (www.opttek.com)	scatter search and tabu search, neural networks
OPTIMIZ (SIMUL8)	Visual Thinking International Ltd. (www.simul8.com)	neural networks
SimRunner (ProModel)	PROMODEL Corp. (www.promodel.com)	evolutionary, genetic algorithms
Optimizer (WITNESS)	Lanner Group, Inc. (www.lanner.com/corporate)	simulated annealing, tabu search

There is no reason to make efforts to prove how efficient and useful the computer simulation is. But the important question that each researcher should ask is: how to gain the maximum results from simulation? This general question can be divided into more detailed ones, e.g. how to make simulation experiments more efficient taking under consideration such factors as time consumption and research simplification (automation). In many cases, especially

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in discrete-event simulation, the good solution can be obtained by using optimization tools. One of those tools is OptQuest for Arena. In this paper the description of OptQuest software is presented. The most important features of OptQuest are described basing on the case of business process example.

2.1. The reasons to use optimization in simulation models

For decades, simulation has been used as a tool to support decision making in many areas of economy. It is far cheaper and faster to build a virtual system and experiment with different scenarios and decisions before actually implementing the system [10]. OptQuest analysis software enhances Arena, allowing the search for optimal solutions in certain simulation models. Many complex simulation models refer to decision making problems where it is important to determine the best values of the input vector variable. When we talk about optimization, it also has the objective function, which plays the role of optimized mathematical formula. This function can be encoded by the optimization software algorithm and by the parameters of the tested model. That is the case OptQuest. An example of OptQuest application in the case described in this paper is a small cinema. The problem is to decide the number of staff required to perform certain tasks while maintaining quantitative restrictions. One of the major limitations of simulation models is that we treat them as so-called "black box", so we cannot expect the software automatically sets the input and output variables. Accordingly, there is a need for independent determination of the vector values that are appropriately selected in the process of simulation and optimization.

Because there are no right tools for the simulation we are forced to choose between searching the optimal solution using heuristics or manual - trying to successfully hit the right solution. There is another method that theoretically gives 100% sure of gaining the optimal solution. It involves counting and checking all possible cases, but often the number possible solutions is so large that even the fastest computers must lead evaluation for years, which in most cases is not an option.

So, using common simulation software, without additional more sophisticated evaluation units, the researcher is forced to search for the best solution manually and intuitively, which usually involves a repetition of the simulation, with a random initial vector of variables, which are modified in subsequent iterations. This process is very time consuming and can be compared to wandering blindly in the dark room looking for exit.

European Commission issued a survey stated that “across sectors, transversal and generic skills will be increasingly valued on the labour market: problem-solving and analytical skills, self-management and communication skills, the ability to work in a team, linguistic skills and digital competences.”[2] This is a proof that the modern techniques of business improvement are in high demand. There are many examples on the use of simulation for manufacturing systems design. They can be found in [6, 9]. Some of them that refer to the use of simulation for manufacturing systems operation can be found in [4]. Methods of computer simulation were used in variety levels and aspects of manufacturing systems such as supply chain management [7], scheduling [8] and the enterprise level [1]. An extensive survey on the use of simulation especially in manufacturing systems modelling can be found in [12].

Many disadvantages of simulation modelling can be removed through the use of OptQuest, which is software that allows defining the input variables, the optimized values and the required constraints. Consequently, without the wide knowledge about the complex methods and optimization procedures, the researcher is able to carry out the optimization process to yield a satisfactory result.

2.2. Way of interaction between OptQuest and Arena

OptQuest main role is to automate and control arena for matching vectors of input values, start and stop each simulation session, as well as reading and interpreting the results of simulation experiments. When OptQuest starts, it checks at the beginning of the current model of the arena, in particular reading defined in the input and output variables. Next, you go to the stage of the optimization process to define the user interface software OptQuest.

Once the optimization is activated, OptQuest sends a signal for Arena. Then the input variables and parameters of quantitative resources that were previously entered by the user are appropriately modified according to the OptQuest guidelines. Then, Arena receives commands for carrying out subsequent replications of simulation experiments. In this way, the software controls the behavior of the Arena OptQuest during optimization. After each replication of the optimization cycle, the outputs of the Arena are forwarded to OptQuest. There are analyzed and determined on the basis of the new values are input parameters the next replication.

It is important that OptQuest sets the input variables only once each time before the next replication. If, therefore, the process of Arena is designed so that during the simulation it changes the parameters of resources, it may cause an unexpected error. Such situation could take place where for example we set the parameters of OptQuest with the aim of reducing the amount of the resource to a certain maximum value, and the Arena causes that this value is exceeded. Such risks make the user should take particular care during planning and designing simulation using OptQuest optimization software.

In recent years, intensive development of information technology has been able to develop a number of effective and efficient optimization methods. Many of them are based on artificial intelligence and use for example genetic algorithms. Optimization techniques are often used in cases where the nature of the problem makes it belongs to the category of so-called NP-hard problems. NP-hard problems cannot be solved in any other way than by calculation and testing all possible combinations of input variables vector. All known simplification consists in extracting from the set of all possible cases, a subset of which, because of its smaller cardinality is possible to iterate evaluation. Proper parameterization of OptQuest allows, among other things, to establish the conditions to stop the iterative process of calculation. The condition of stop may be such as the duration of the simulation, the number of replications or the lack of improvement in the objective function results in subsequent iterative steps.

Such optimization techniques not always allow finding the optimal solution, but almost always it is possible to find a solution similar to it or at least a satisfactory from the point of view of the particular application.

2.3. Analyzing business organization with OptQuest for Arena: A case study of Movie Theatre design

Mentioned below example describes the Movie Theatre. The management of the theatre is determined to create efficient organization where the main goal is to maximize the profit. Customers arrive to the cinema and they purchase tickets and refreshments. The cinema organization earnings are taken mainly from such sources like selling tickets and refreshment. Of course there are not only ways to get money. Sometimes the movie theatre organizes the private events, presentations, conferences etc. but those elements will be omitted in simulation. The main purpose of the cinema activity is selling tickets and refreshment. If so, the management objective is to identify and organize all the necessary resources in the optimal system.

In our case three kinds of human resources were identified: Main Refreshment Staff, Satellite Refreshment Staff and Ticket Takers (Tab. 2.2).

Tab. 2.2. Resources of the Movie Theatre

Staff	Lower Bound	Current Staffing	Upper Bound
Main Refreshment Staff	1	2	6
Satellite Refreshment Staff	1	1	6
Ticket Takers	1	2	5

The capacities of the resources will be used as controls. Each kind of the resource has assigned value that can be changed in individual iteration. A set of values of the resources that is used in given iteration makes a vector of values. Then, we can say that the result we expect from OptQuest is to identify of the best vector of values, which allows obtaining the optimal (maximal) profit. In such a way the reworked model tracks the total profit from described movie theatre operations.

Before we start OptQuest, first of all we have to build the base model with Arena Rockwell. Only then it will be reasonable to run OptQuest. The logic of Arena allows dividing whole model into sub models. Such division makes easier orientation and navigation among individual elements of the model (Fig.2.1).

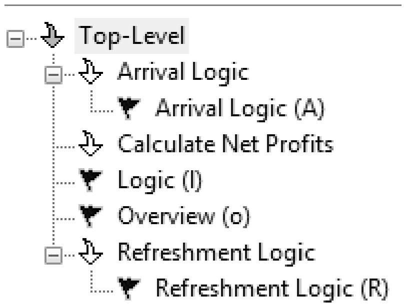

Fig. 2.1. Top-down structure of the model

The model of the movie theatre consists of three sub models: Arrival Logic, Refreshment Logic and Calculate Net Profits (Fig.2.2).

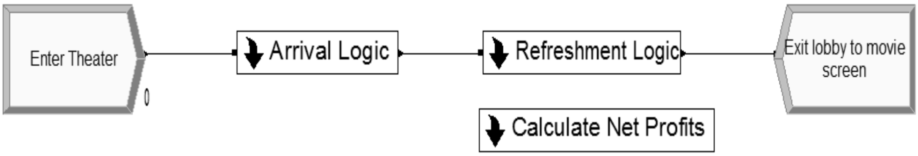

Fig. 2.2. Top-level view of the model

Arrival Logic sub model controls the flow of the customers within the cinema (Fig. 2.3). Usually, customers resign from purchase tickets when the line is too long. This case is enclosed in decision symbol “Is line too long?” This instruction makes customers balk when the number in line (Queue) double exceeds the Max Waiting Line Length. Record “Number leaving ticket line” counts the number of patrons who decide to go elsewhere so they are lost for us. This counter will be exploited in future analysis.

Process “Get Ticket” allows the customers to purchase their ticket and “Gross Profit Assignment” increments the Gross Profit calculation (Fig.2.3). This assignment is achieved according to simply formula:

```
Gross Profit = Gross Profit + 1.50
```

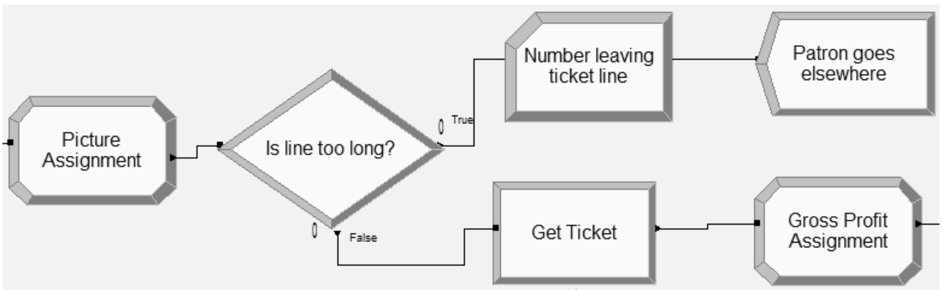

Fig. 2.3. Arrival Logic

Refreshment Logic subsystem is applied for each patron who has already purchased the ticket (Fig. 2.4). First of all we have the decision “Hungry?” that makes about 80% of customers want to buy refreshments. Next step is the decision stage “Go to main stand?” which compares the number of people waiting in line before Main refreshment stand to the chosen value according to the following relationship:

```
NQ(Main refreshment stand.Queue) < Max Waiting Line
Length
```

where: NQ (Queue ID) is the Number in queue. NQ returns the number of entities in queue Queue ID.

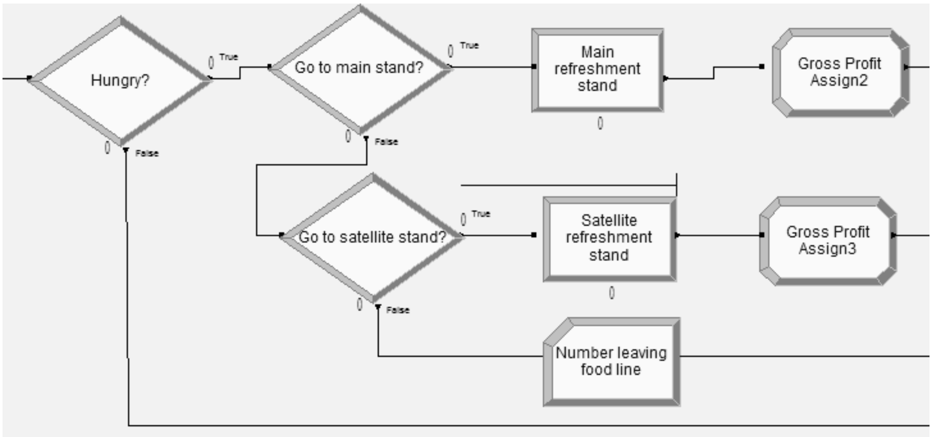

Fig. 2.4. Refreshment Logic

In the model Max Waiting Line Length variable is used to determine if the customer will wait in the Main Refreshment Stand line. The customers who resign from Main Refreshment Stand go to Satellite Stand. Decision “Go to satellite stand?” compares the number of people waiting in line with the variable Max Waiting Line Length to determine if the customer will wait in the Satellite Refreshment Stand line and checks to see if the Satellite Refreshment Stand is staffed according to the following relationship:

```
(NQ(Satellite refreshment stand.Queue) < Max Waiting
Line Length) .AND. MR(Satellite refreshment Staff) > 0
```

where: MR (Resource ID) is Resource capacity. MR returns the number of capacity units currently defined for the specified resource. The Alter module or Schedules option may be used to change the value of MR for a resource. MR is an integer quantity.

Processes “Main refreshment stand” and “Satelite refreshment stand” allow customers to purchase refreshments at the Main or Satellite stand, and to increment the Gross Profit calculation. The “Number leaving food line” record counts the number of patrons who decide to not purchase refreshments. The researcher can use this counter in his further analysis. “Main refreshment stand” stops patrons for some time. At this point important is a factor called Delay Type which is type of distribution or method of specifying the delay parameters. Constant and Expression require single values, while Normal, Uniform and Triangular require several parameters. In presented case the same triangular distribution was implemented for both processes “Main refreshment stand” and “Satelite refreshment stand”, and the parameters mentioned in Tab. 3 were entered.

Tab. 2.3. Parameters of triangular distribution

Description	Value [min]
Minimum	2
Most likely	4
Maximum	7

After visiting the main or satellite stand the each purchasing case increments profit according to the following formula:

```
Gross Profit+ UNIF(.75,2)
```

where: UNIF(.75,2) means that the random uniform distribution was adopted. This function returns a random real value between 0.75 and 2.

Such prepared with Arena Rockwell model can be further processed with more sophisticated tools like OptQuest. Just after we chose menu “Tools” → “OptQuest for Arena” the new window appears. The user can chose one of the two buttons: “Browse…” or “New Optimization”. If we already have the previously saved optimization file that can be evoked for further processing we should chose “Browse…” button. “New Optimization” button is suitable for the new projects. Interesting thing is a fact that in Central European issues of Microsoft Windows operating systems where usually decimal separation symbol is comma “,” the user should enter Control Panel and change comma to dot “.”. Otherwise OptQuest shows an error message.

When we chose “New Optimization” button, a new window appears. The window is vertically divided into two panels. Left pane includes the tree menu through which researcher can quickly enter the desired view. Right panel always shows the proper user interface referring to chosen option in the left panel. At the beginning we should chose “Resources” in the left pane and find our three kinds of human resources that were previously established in Arena. After that we must click the proper check boxes to indicate that those kinds of staff should be selected to optimization.

We have to remember to enter modifications of bounds and suggested values for each of the resource controls according to information mentioned in Tab.2.2. Especially the proper modifications of Lower Bound, Current Staffing and Upper Bound must be done (Fig. 2.3).

Controls Summary

Includ	Category	Control	Element Type	Type	Low Bound	Suggested Value	High Bound	Step
☑	Resources	Main Refreshment Staff	Resource	Discrete	1	2	3	1
☑	Resources	Satellite Refreshment Staff	Resource	Discrete	1	1	2	1
☑	Resources	Ticket Takers	Resource	Discrete	1	2	3	1

Fig. 2.3. Controls summary of simulation with constraints

Next step is to open the Responses Summary window by selecting the Responses node from the tree view or clicking View → Responses menu to show the resulting values or outputs from the Arena simulation. This output cannot be modified. However, the main goal of top management is to maximize net profit, so we should select the Net Profit variable by checking the corresponding box in the included column [13].

After that we can display the Constraint Summary grid by selecting the Constraints node from the tree view or clicking View → Constraints menu (Tab. 2.4).

Tab. 2.4. Constraints summary

Name	**Expression**
Leaving Ticket Line	[Number leaving ticket line] = 0
Leaving Food Line	[Number leaving food line] <= 10
Total Staff	[Main Refreshment Staff] + [Satellite Refreshment Staff] + [Ticket Takers] <= 10

As we see in Tab. 4 there are limitations referring to the length of the lines. One of our goals is to have no customers who buy the ticket because of too long queue. Another objective is to have less than 11 customers that resign from the refreshment for too long line. The last constraint limits the total number of our staff to less than 11. All those restraints let the OptQuest to change variables and controls to maximize net profit but not by all means.

Finally we should define the main objective. In our case it is Net Profit. It is very important to check “Maximize” option (Fig. 2.4).

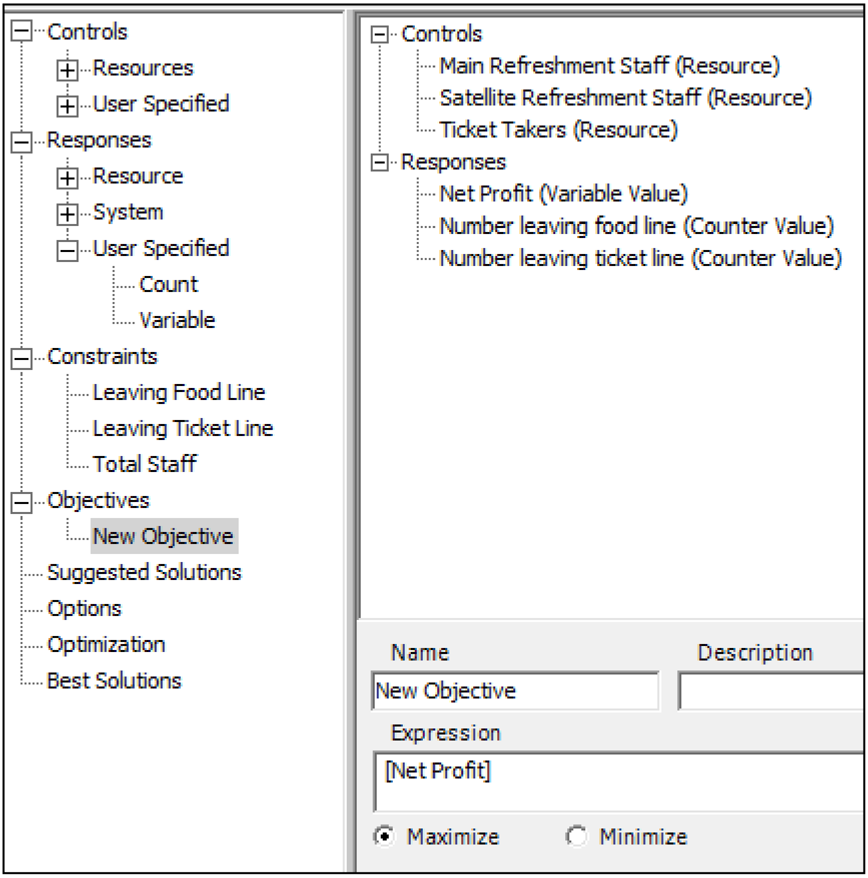

Fig. 2.4. Navigation tree

As it is presented in Fig. 2.4 the navigation tree structure includes eight main items: Controls, Responses, Constraints, Objectives, Suggested solutions, Options, Optimization and Best Solutions. It should be noticed that two last items are visible only after the optimization process is done. The Controls item consists of two sub items: Resources and User Specified. In our case resources are mentioned in Fig. 3. User specified controls are the following variables: Gross Profit, Max Waiting Line Length and Net Profit.

The Responses item consists of three sub items: Resource, System and User Specified. Resource type Responses refers to the values of the defined resources. They include such parameters as costs, time and number of customers. Analogously, the System type Responses refers to the similar values but always in relation to all resources in the model. The User Specified Responses are divided to two groups: Count and Variable. Constraints and Objectives are the elements that can be added and defined by the OptQuest user. They can be added, modified or deleted.

The last thing should be done before starting simulation is to set proper options. In this case we tested two option cases (I and II). In the first option case the following indicators were switched on: Manual Stop, Tolerance 0.00001, Number of Replications per Simulation: 10. The results of the simulation experiment for this case is shown in Fig.5. In the second option case the following indicators were switched on: Automatic Stop, Tolerance 0.0001, Number of Replications per Simulation: 3. The results of the simulation experiment for this case is shown in Fig. 2.6.

It can be seen that there is a small difference between both results. In the first case the objective value (Net Profit) was 1139 USD. In the second case the objective value was 1138 USD. The difference is really minimal. Some differences are visible in the quantity of the three kinds of staff (Tab. 2.5).

Tab. 2.5. Best values for Resources

Type of staff	Option case I	Option case II
Main Refreshment Staff	5	2
Satellite Refreshment Staff	1	4
Ticket Takers	2	2
Sum:	8	8

There are differences between quantities of all kinds of staff but in both cases the total number of employees equals eight. The number of simulation experiments was always 102, but the best simulation was conducted in the first case after 66 iterations and in the second case after 77 iterations. This is interesting thing if we consider the fact that e.g. the Number of Replications per Simulation in the first case was 10 and in the second case was 3. Considering this we could expect that the much better result should be obtained in the first case. Meanwhile, both results are almost equal.

Optimization **Completed Optimal solution found.**

Total simulations: 102

Best Simulation 66

Maximize		
	Objective Value	**Status**
Best Value	1139.277798	Feasible
Current Value		

Controls		
Control Name	**Best Value**	**Current Value**
Main Refreshment Staff	5	
Satellite Refreshment Staff	1	
Ticket Takers	2	

Constraints		
Constraint Name	**Type**	**Status**
Leaving Food Line	Non Linear	Feasible
Leaving Ticket Line	Non Linear	Feasible
Total Staff	Linear	Feasible

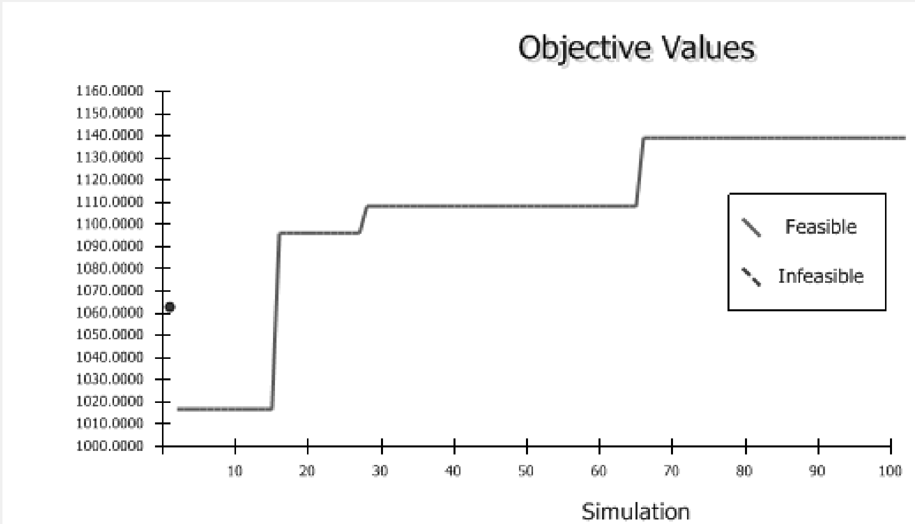

Fig. 2.5. Solution of simulation with constraints – options case I

Optimization **Completed Optimal solution found.**

Total simulations: 102

Maximize		
	Objective Value	**Status**
Best Value	1138.156576	Feasible
Current Value		

Best Simulation 77

Controls		
Control Name	**Best Value**	**Current Value**
Main Refreshment Staff	2	
Satellite Refreshment Staff	4	
Ticket Takers	2	

Constraints		
Constraint Name	**Type**	**Status**
Leaving Food Line	Non Linear	Feasible
Leaving Ticket Line	Non Linear	Feasible
Total Staff	Linear	Feasible

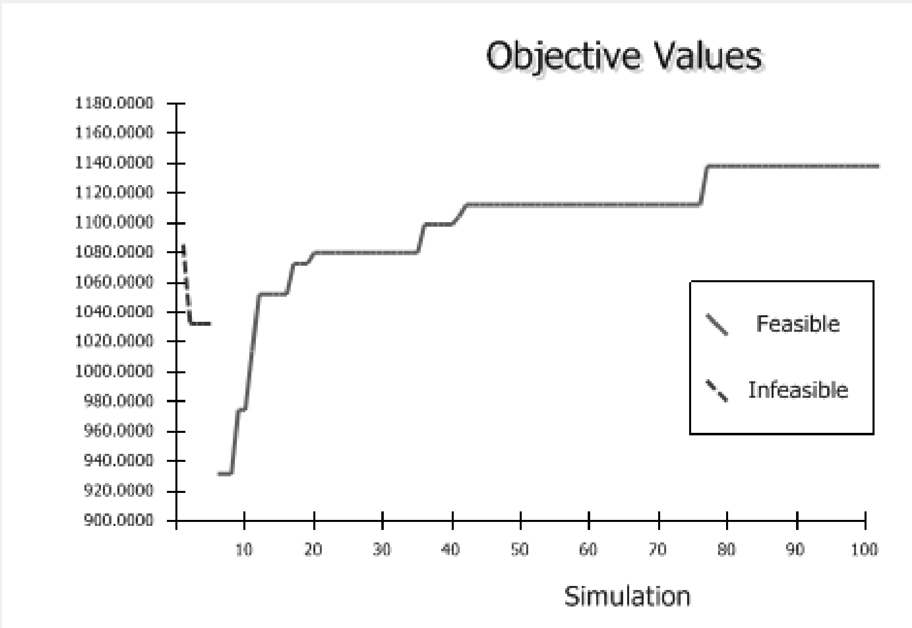

Fig. 2.6. Solution of simulation with constraints – options case II

There is the question why in spite of more robust options that was set in the case I, the results are similar. The answer could refer to a few aspects. Maybe some of them can be connected with the individual approach to each problem. Yet, the individual treating of each case could be troublesome because it is much better to discover the one or few general rules suitable for all cases. During many optimization experiments some conclusion was drawn. First of all it appears that there are many different factors that influence the optimization performance. Usually the researches expect high-quality solutions obtained as quickly as possible. Evaluating performance of the example presented in this paper, we look forward to OptQuest finds a solution with a large profit and it quickly jumps to the range of high-quality solutions. The best solutions of case I of simulation with constraints are shown in Fig. 2.7.

Best Solutions Optimal solution found.

Select	Simulation	Objective Value	Status	Main Refreshment Staff	Satellite Refreshment Staff	Ticket Takers
☐	66	1139.277798	Feasible	5	1	2
☐	28	1108.261986	Feasible	2	4	2
☐	44	1105.636474	Feasible	3	3	2
☐	16	1096.214534	Feasible	4	2	2
☐	35	1086.580665	Feasible	5	1	3
☐	67	1083.960313	Feasible	1	5	2
☐	49	1080.731369	Feasible	6	1	2
☐	46	1079.386910	Feasible	4	3	2
☐	31	1077.281032	Feasible	5	2	2
☐	26	1069.468453	Feasible	4	2	3
☐	29	1063.590523	Feasible	3	4	2
☐	37	1062.531584	Feasible	3	3	3
☐	25	1050.892093	Feasible	5	1	4
☐	23	1047.122004	Feasible	4	2	4
☐	71	1046.149671	Feasible	2	5	2
☐	51	1045.025663	Feasible	1	6	2
☐	60	1042.874366	Feasible	6	2	2
☐	34	1041.743570	Feasible	2	4	4
☐	41	1035.532567	Feasible	1	5	3
☐	22	1034.987138	Feasible	5	2	3
☐	43	1034.575858	Feasible	2	4	3
☐	39	1034.050988	Feasible	3	4	3

Fig. 2.7. Best solutions of simulation with constraints – options case I

Apart from this, observing the drawings in Figs. 5 and 6, the clear difference of the line shape is noticeable. As we mentioned above, heuristic methods allows finding the suboptimal solutions, so there is no guarantee that the given solution is the best. Because of this reason it is important to for OptQuest to make big improvement at the first part of simulation and then, already having solution close to the optimal value, try to improve it. There are the following factors that directly affect the search performance: Number of controls, Initial values, Bounds and constraints, Complexity of the objective, Feasibility, Number of replications and simulations, Simulation accuracy, Simulation speed.

Another aspect that affects to the optimization performance is the number of controls. According to general rule the more controls is defined in the model the more simulations is needed to obtain satisfactory result (Tab. 2.6).

Tab. 2.6. Number of controls vs. minimum number of simulations

Controls	Minimum number of simulations
Fewer than 10	100
Between 10 and 20	500
Between 20 and 50	2000
Between 50 and 100	5000

Conclusions

In this paper the problem of enhancing the optimization capabilities of simulation software with OptQuest for Arena Rockwell was presented. OptQuest is a tool for conducting the optimization experiments and is dedicated to enhance Arena capabilities. The point is to use this sophisticated tool in proper way. The relevant example problem was resolved. The short description of the important matters of Arena preparation was shown. The step-by-step instruction regarding using and customizing OptQuest was brought up. Basing on the presented case the handling of OptQuest tool was presented and the results are discussed. It is quite obvious that such optimizing tools as OptQuest are very useful but their performance largely depends on skills and experience of the researcher who must know the rules between variety options and controls of the evaluated model. Some of those rules was presented and discussed in this paper.

References

[1] Arafa A., ElMaraghy W.: Manufacturing strategy and enterprise dynamic capability. CIRP Annals-Manufacturing Technology, 2011.

[2] European Commission (2010): Better matching and anticipating labour market needs. http://bit.ly/14At58X (access 27-03-2013).

[3] Fu M.C., Smith R. H.: Optimization for Simulation: Theory vs. Practice, Journal on Computing, Vol. 14, No. 3, 2002, pp. 192–215.

[4] Gupta M., et al.: Operations planning and scheduling problems in advanced manufacturing systems. International Journal of Production Research, 1993. 31(4): pp. 869-900.

[5] Kelton W. D., Sadowski R. P., Sadowski D. A.: Simulation with Arena. 2nd ed., London: McGraw-Hill, 2002.

[6] Law, A.M. and McComas, M.G. Simulation of manufacturing systems. 1999: ACM.

[7] Pathak S., Dilts D: Simulation of supply chain networks using complex adaptive system theory. 2002: IEEE.

[8] Sabuncuoglu I.: A study of scheduling rules of flexible manufacturing systems: a simulation approach. International Journal of Production Research, 1998. 36(2): pp. 527-546.

[9] Schroer B. J., Tseng, F.T.: Modelling complex manufacturing systems using discrete event simulation. Computers & industrial engineering, 1988. 14(4): pp. 455-464.

[10] Seleima A., Azaba A., AlGeddawya T.: Simulation Methods for Changeable Manufacturing, Procedia CIRP 3 (2012) pp. 179 – 184.

[11] Simulation Software Survey: http://bit.ly/10pLGzl (access 27-03-2013).

[12] Smith, J.S.: Survey on the use of simulation for manufacturing system design and operation. Journal of manufacturing systems, 2003. 22(2): pp. 157-171.

[13] User’s Guide, Publication Arenao-UM001H-EN-P–January 2012.

ENHANCING THE OPTIMIZATION CAPABILITIES OF SIMULATION SOFTWARE WITH OPTQUEST FOR ARENA ROCKWELL

Abstract: This article concerns the use of OptQuest simulation software, aimed at the business processes optimization. Based on the practical example it shows how to work with the mentioned above software tool to create a model based on Arena Rockwell. The model is subjected to optimization in order to find the best solution. Described case allows researcher to become better acquainted with the advantages and potential problems that the he may encounter when working with OptQuest software. In discussed case two variants of the optimization processes were presented. Those variants differ in settings of initial parameters that determine the course of experiment. As a result, it was possible to compare the influence of the above-mentioned differences on the final result, which was profit optimization of the modeled business. The goal of the optimization was obtaining information regarding the appropriate values of the variables that affect the profit. The iteration way of obtaining the best result in two variants with OptQuest was presented. It allowed detecting the differences that could occur during simulation process according to set-up of initial conditions.
Key words: Simulation, Optimization, Software Tools

WSPARCIE ZDOLNOŚCI OPTYMALIZACYJNYCH OPROGRAMOWANIA SYMULACYJNEGO Z ZASTOSOWANIEM OPTQUEST DLA ARENA ROCKWELL

Streszczenie: Niniejszy artykuł dotyczy zastosowania oprogramowania symulacyjnego OptQuest, ukierunkowanego na optymalizację procesów biznesowych. W oparciu o praktyczny przykład, zaprezentowano sposób pracy z programem przy tworzeniu modeli na bazie oprogramowania Arena Rockwell. Opracowany model zostaje poddany optymalizacji w celu znalezienia najlepszego rozwiązania. Opisany przykład umożliwia lepsze poznanie zalet, a także z potencjalnych problemów, jakie może napotkać badacz podczas pracy z oprogramowaniem OptQuest. W omawianym przykładzie przedstawiono dwa warianty procesu optymalizacji, różniące się ustawieniem parametrów początkowych, określających dalszy przebieg eksperymentu. Dzięki temu, możliwe było dokonie porównania wpływu ww. różnic na rezultat końcowy, jakim była optymalizacja zysku modelowanego przedsiębiorstwa. Celem optymalizacji było uzyskanie informacji odnoście odpowiedniego doboru wartości pewnych ustalonych zmiennych, mających wpływ na wysokość zysku. Zaprezentowano iteracyjny sposób dochodzenia oprogramowania OptQuest do najlepszego rozwiązania w obu wariantach. Dzięki temu, można lepiej dostrzec różnice w działaniu oprogramowania symulacyjnego w zależności od pierwotnie wybranych warunków procesu.

Słowa kluczowe: symulacja komputerowa, optymalizacja, oprogramowanie symulacyjne

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3. Structural and behavioural system periodicity

Introduction

A periodic structure may be defined as an assembly of an object that repeats regularly in space [9]. In other words, the periodic structure is made of a basic object that repeats at precise intervals in space and the resultant structure possesses regularity. Examples of periodic structures include scaffold structures or building frameworks where the constituent objects (e.g. routes and intersections, see Fig. 3.1 showing the Manhattan quarter) are regularly distributed in space and all have the same size.

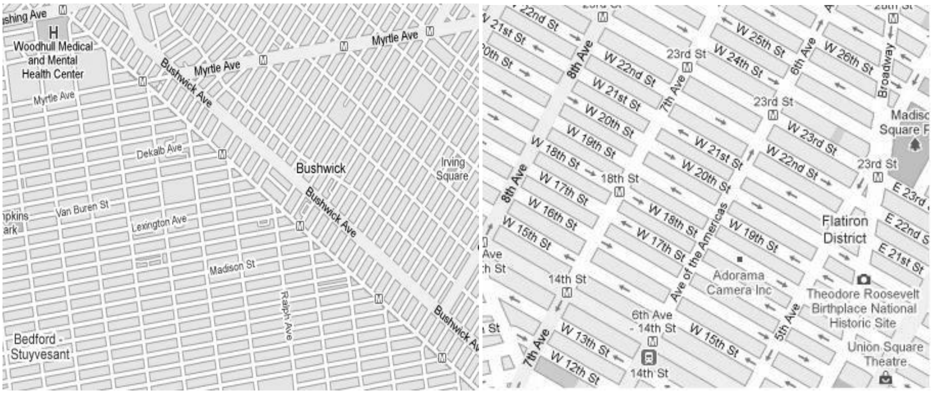

Fig. 3.1. Fragment of the map of lower Manhattan [http://maps.google.com]

Consider a periodic structure system composed of a set of elementary objects (each of which is identical in size and cyclic shape) providing "guideways" for local cyclic processes. Example of such solution follows from networks composed of Personal Rapid Transit or Automated Guideway Transit [6] systems as well as flow shops with rotary and/or carousel transportation. In that context, we are interested in how the geometry of a periodic structure, providing local cyclic processes guideways, determines the resultant behavioral properties of the whole system.

Assuming that in the case of periodic structure systems, only a single computational sample needs to be studied because the sample precisely describes the periodic system behavior, we are looking for a method allowing us to predict the behavioral properties of periodic structures, which in turn allow us to design, understand, and optimize the structures prior to their final

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application. In order to illustrate an idea standing behind of that approach let us consider the following question: is it possible to organise street traffic (based on traffic lights) in any city so as to ensure a green wave for each street and in each direction? Looking at Fig. 3.2a) which illustrates the mechanism of a green wave, it is easy to observe that the answer is in the affirmative, if we assume regularity of the transport infrastructure (Fig. 3.2b). The considered problem of street traffic organisation, belongs to the group of problems strongly dependent on the structure of the described object (in this case, a city). As it was observed, the symmetrical structure of streets allows to plan a fair (unbiased) system of traffic lights.

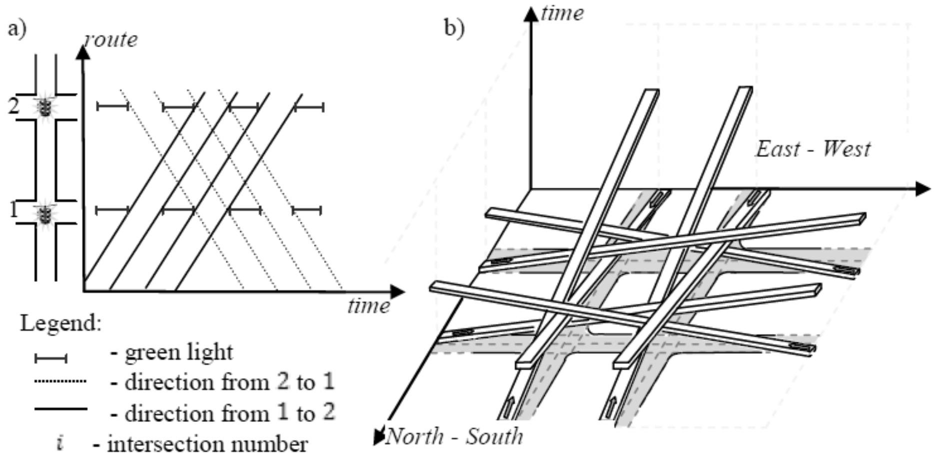

Fig. 3.2. Illustration of street traffic implementing a green wave

We belief this approach can be useful in problem solving concerning cycle time minimization in the repetitive manufacturing flow-line system with no store constraints, which provides the fixed mix of various products on the system output. Note, that minimal cycle time is not a regular criteria and the considered cyclic job shop scheduling problem, is strongly NP-hard [8]. Similarly to the above mentioned AGVs fleet match-up scheduling problem providing conditions allowing one to adjust the AGVs fleet schedule due to the timetable of operations executed in an assumed multi-product manufacturing environment can be considered as well [3,4].

In other words we believe our approach provides an promising alternative for many models and methods have been considered so far [8]. Among them, the mathematical programming approach [1, 13], max-plus algebra [10], constraint logic programming [3, 4, 5] evolutionary algorithms [7, 11], Petri nets [12] frameworks belong to the more frequently used. Most of these are oriented at finding of a minimal cycle or maximal throughput while assuming deadlock-free processes flow. It seems to be obvious, that not all the behaviors (including cyclic ones) are reachable under constraints imposed by the system's structure.

The similar observation concerns the system's behavior that can be achieved in systems possessing specific structural constraints. Since system constraints determine its behavior, both the system structure and the desired cyclic schedule have to be considered simultaneously. In that context, our contribution provides a discussion of some solubility issues concerning cyclic processes dispatching problems, especially the conditions guaranteeing solvability of the cyclic processes scheduling. Their examination may replace exhaustive searches for solution satisfying required system capabilities.

The rest of the paper is organized as follows: Section 2 provides illustrative examples of structure depended system behaviors. Section 3 formulates a problem statement. Then the mesh-like approach to concurrent process cyclic scheduling is considered in Section 4. Concluding remarks are presented in Section 5.

3.1. Illustrative Examples

Let's consider the most common and intuitive example a toothed gear transmission (see Fig. 3.3) [3].

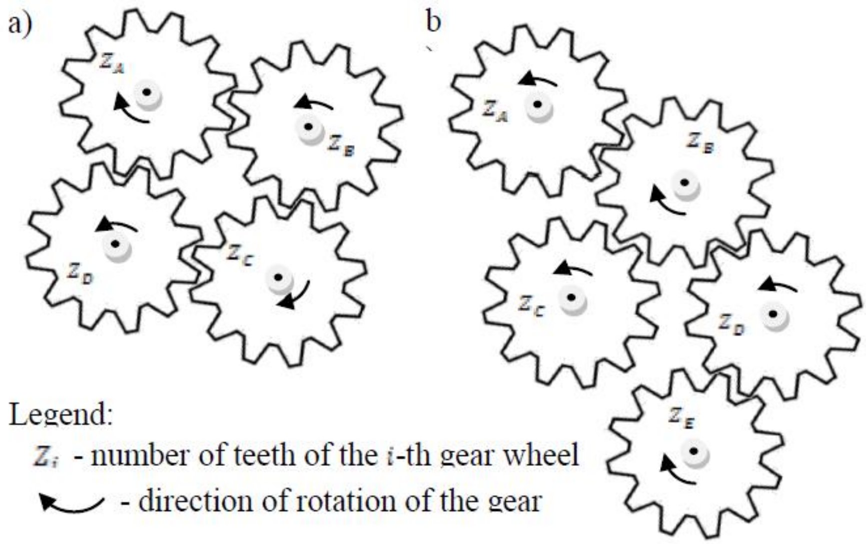

Fig. 3.3. Examples of toothed gear transmissions: a closed a) and open b) structure

Assuming that the gear wheels A, B, C, D, E have 20, 30, 15, 25 and 40 teeth, respectively, the transmission ratio for the gear transmission with an open structure (Fig. 3.3b), consisting of two levels of gears $A-B$ and $B-C$, is $20/30 \cdot 30/15 = 1.33$; whereas for $A-B$, $B-D$, and $D-E$, is $20/30 \cdot 30/15 \cdot 15/40 = 0.5$, i.e. for every two turns of wheel A, there is one full turn of wheel E. Clearly, for the gear transmission with a closed structure (Fig. 19.3a)), the transmission ratio can be described by the relation:

$$\frac{Z_A}{Z_B} \cdot \frac{Z_B}{Z_C} \cdot \frac{Z_C}{Z_D} \cdot \frac{Z_D}{Z_A} = 1 , \tag{3.1}$$

where: Z_i is the number of teeth of the i-th gear wheel, and $Z_i \in \mathbb{N}$.

When looking for the time period T for the considered system, the following equations must be taken into account:

$$x \cdot Z_A = T; y \cdot Z_B = T; z \cdot Z_C = T; u \cdot Z_D = T , \tag{3.2}$$

where: $x, y, z, u \in \mathbb{N}$ – the numbers of full revolutions performed in time period T. Clearly:

$$T = LCM(Z_A, Z_B, Z_C, Z_D) . \tag{3.3}$$

It's worth noticing that calculating a period as the least common multiple (LCM) of the number of teeth of subsequent gear wheels multiplied by the number of rotations performed by gear wheels in the time period of the system means that the time period of the system of gear wheels can be expressed in terms of the number of teeth. In other words, the period of a gear system is determined by the number of teeth by which the wheels of the system must rotate so that each of them performs a full number of turns.

In the case, where $x = y = z = u = n$, Eqs. (1) and (2) necessitate the use of four identical gear wheels $Z_A = Z_B = Z_C = Z_D$. In the general case, the values of the full turns x, y, z, u that satisfy Eqs. (1) and (2), correspond to the cyclical behaviour of the system for given Z_A, Z_B, Z_C, Z_D.

To sum up, according to the elementary laws of kinematics, the transmission gears with a closed structure must contain an even, $n \geq 4$ number of gear wheels, with a number of teeth and their mutual relation satisfying Eq. (2), (3). With this satisfied, we can attempt to answer the remaining questions, e.g. with a given number of teeth for each gear wheel (local periods), is it possible to construct a transmission gear with a given time period?

From this perspective, a Diophantine problem of looking for a set of wheels that would guarantee a time period T can be formulated as follows (note that the function $F = LCM(.)$ is not a polynomial):

Given are: n – number of gear wheels, T – time period of the system, $Z = \{Z_1, Z_2, \dots, Z_n\}$ – a set that contains the number of teeth of the wheels, $Z_i \in \mathbb{N}$. The set Z is composed of two disjoint subsets A and B. Assuming that $n \in \mathbb{N}$, $Z_i \in \mathbb{N}$, $A, B \subseteq Z$, $A \cup B = Z$, $A \cap B = \emptyset$, $T = LCM(Z_1, Z_2, \dots, Z_n)$, the response to the following question is sought: For the given set of wheels A, is there any set of wheels B that would guarantee that the entire system would have a time period T?

Let's try to analyse several examples which will help convince us that this problem is decidable. Given is a set of three gear wheels with the following numbers of teeth: $Z_1 = 10$, $Z_2 = 20$, $Z_3 = 30$ (set A). Is it possible to find such a wheel (set B), whose number of teeth Z_4 would guarantee that the system would have time period T? According to the assumed formulation of the problem, the answer boils down to solving the following equation:

$$180 = LCM(10, 20,30, Z_4)\ . \tag{3.4}$$

Clearly, the solution is $Z_4 = 90$. However, in general, achieving this sort of behaviour might not be possible.

Let's consider another example: given is a set of three gear wheels (set A) with the following numbers of teeth: $Z_1 = 10, Z_2 = 25, Z_3 = 30$. Is it possible to find such a wheel (set B), whose number of teeth Z_4 would guarantee that the system would have a time period $T = 180$?

$$180 = LCM(10, 25,30, Z_4)\ . \tag{3.5}$$

In this case, the solution doesn't exist. In order to reach this conclusion, we don't have to substitute the subsequent numbers from the set of natural numbers. It suffices to apply the following (obvious) condition (3) – the solution exists if the number of teeth of each gear wheel is a divisor of the time period *T*. This condition is not satisfied for the third wheel: 25 is not a divisor of 180. The existence of a procedure that always allows to explicitly determine the solution of the presented problem means that here again, we deal with a decidable problem (a decidable Diophantine equation).

It's worth noticing that in the considered two cases, the issue of the structure of the gear systems was entirely omitted. Does, and if so, then in what way, the arrangement of wheels affect the time period of the entire system? Fig. 3.4 presents three systems of wheels from the first example. Clearly, each of them works with the same time period $T = 180$. Analysing the remaining possible variants, we can quickly conclude that if a structure is permissible (i.e.it doesn't contain substructures forming cycles with odd numbers of wheels), it affects neither the period T, nor the transmission of the wheels. This is a rare feature, characteristic only of simple systems.

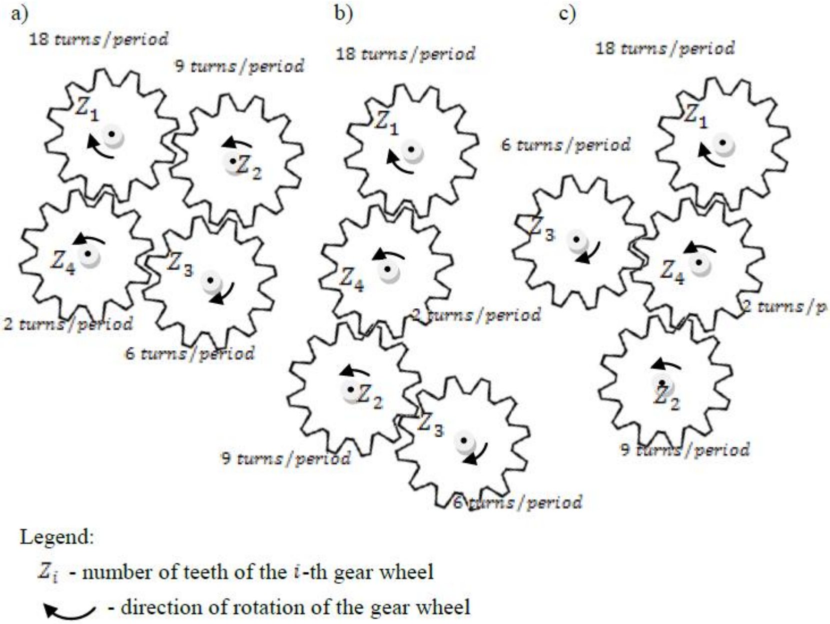

Fig. 3.4.Examples of structures of gear wheels with
$\boldsymbol{Z_1 = 10, Z_2 = 20, Z_3 = 30, Z_4 = 90}$

This helps explain the mysteries of gearboxes and of the functioning of "ticking" clocks. We must get used to the thought that in order to obtain proper transmissions in a small wristwatch, i.e. to ensure that a minute consists of 60 seconds, an hour of 60 minutes, and a day (and night) of 24 hours, it must contain a maze of gears. What is more, their number, size and the connections between them are far from being dictated by chance.

Let's consider the tram routes from Fig. 3.5 and the following problem related to them. The region S, representing the layout of a city, divided into square sectors, respectively, $s_{1,1}$, $s_{1,2}$, …,$s_{1,8}$, $s_{2,1}$,…, $s_{4,8}$, where: $s_{i,j}$ is the sector located in the i-th row and j-th column. Four transportation routes (e.g. tram routes) denoted as I, II, III, IV, together with stops. Assuming that each transportation route constitutes a closed loop, and that transportation in this city can take place only along transportation routes and along the direction denoted in the picture as well as that changes can take place only in sectors common for the given routes and the travel time $t(s_{a,b}, s_{c,d})$ between two sectors $s_{a,b}, s_{c,d}$ is calculated as a number of sectors that must be traversed from sector $s_{a,b}, s_{c,d}$ using an unlimited number of routes the response to the following question is sought: What is the shortest travel time between sectors $s_{4,4}$ and $s_{1,4}$ (denoted by), as well as between sectors $s_{3,1}$ and $s_{3,8}$ (denoted by )?

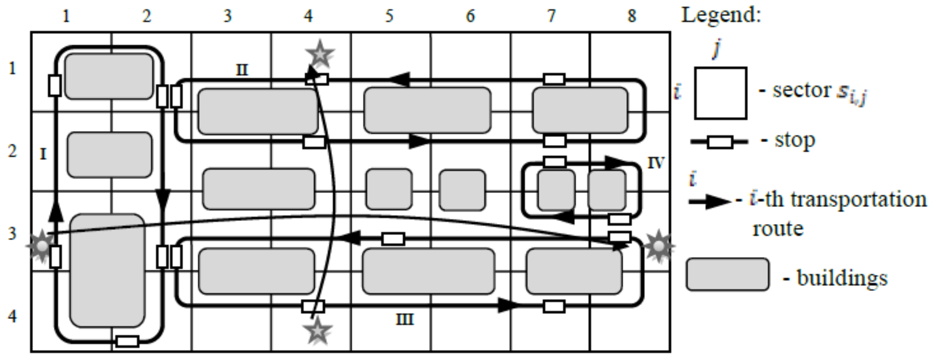

Fig. 3.5. Tram routes in a built-up area

Assuming the duration of a change is assumed to be equal to zero, we can easily find the answer by means of a quick analysis of available connections (there aren't many). The shortest travel time between sectors $s_{4,4}$ and $s_{1,4}$ is 13: $t(s_{4,4}, s_{1,4}) = 13$, (the route denoted by a dot-dashed line, Fig. 3.6a), whereas between sectors $s_{3,1}$ and $s_{3,8}$ – 11: $t(s_{3,1}, s_{3,8}) = 11$ (the route denoted by a dashed line, Fig. 3.6b).

Since we already have some idea about the performance of the available communication system – is there any way to improve it? Let's assume that for some egoistic reasons, we wish to improve the connection between sectors $s_{4,4}$ and $s_{1,4}$. These sectors are separated by only 4 sectors, but it takes 13 arbitrary units of time to travel between them.

For the area *S* as in Fig. 3.5 – is it possible to reorganise traffic so that expected travel time is $t(s_{4,4}, s_{1,4}) < 13$, with the number of tram routes kept? constant?

This means that we allow changing the tram routes, but not their number. We can find the right solution almost immediately. Moving route IV as in Fig. 3.6b) we obtain the travel time $t(s_{4,4}, s_{1,4}) = 7$ (the route denoted by a dot-dashed line, Fig. 3.6b)). Unfortunately, this comes at a price of making the route between $s_{3,1}$ and $s_{3,8}$ longer, from 11 to 13 and also, what is even worse, increasing the travel time between sectors $s_{2,7}$ and $s_{3,8}$ to 14 (instead of 2).

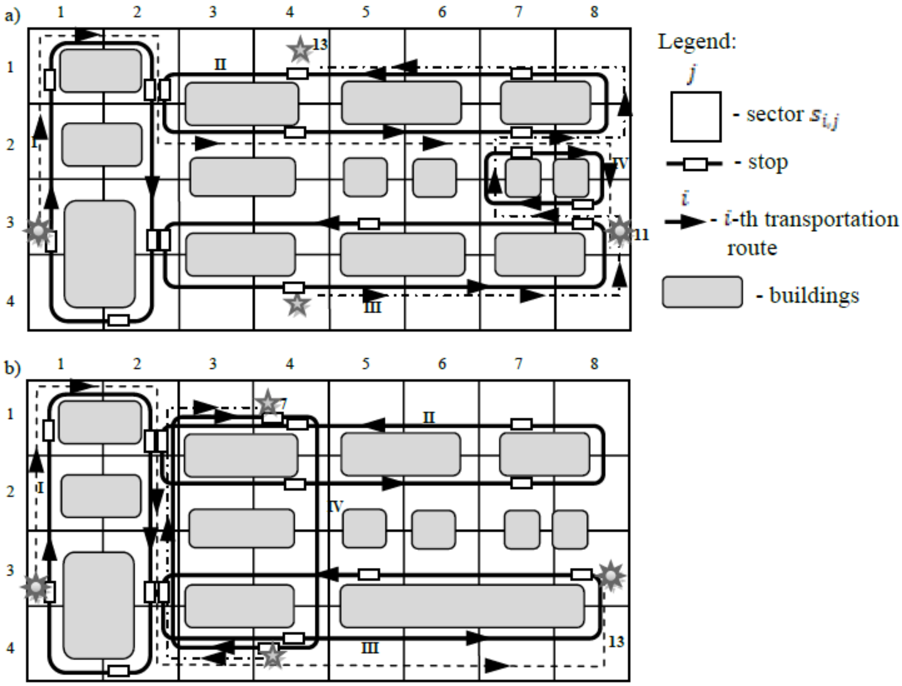

Fig. 3.6. Example of traffic organisation

Ideally, it would be possible to move from each sector (in which there is a stop) to another sector in a time not longer than dictated by the distance between the sectors. Therefore, is it possible, by varying only the tram routes and not their number, to organise traffic in such a way that the travel time between any two stops would be equal to the number of sectors that separate them?

In other words, the traffic must be organised so that: $t(s_{4,4}, s_{1,4}) = 4$, $t(s_{3,1}, s_{3,8}) = 8$, $t(s_{2,7}, s_{3,8}) = 2$, etc. How can this be achieved with only 4 tram routes? Is this not impossible? In the presented example we dealt with a situation in which the improvement of one connections resulted in making another worse. Moreover, the obtained solutions are correct only for the structure for which they were determined. Therefore, we can hardly expect ideal solutions – unfortunately, in this case, only compromises could constitute universal solutions.

Fig. 3.7 shows an example of a transportation system for Flexible Manufacturing System (FMS). Three transportation trucks P_1, P_2 and P_3 move between sectors according to assigned transportation routes in a warehouse. At a given time, only one truck can be loaded or unloaded in a given sector. Access to shared sectors R_1, R_3, R_5 is determined by priority dispatching rules.

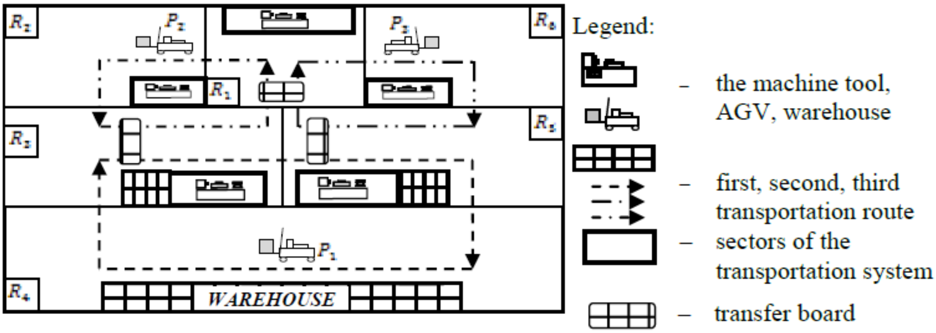

Fig. 3.7. Transportation subsystem of flexible production systems

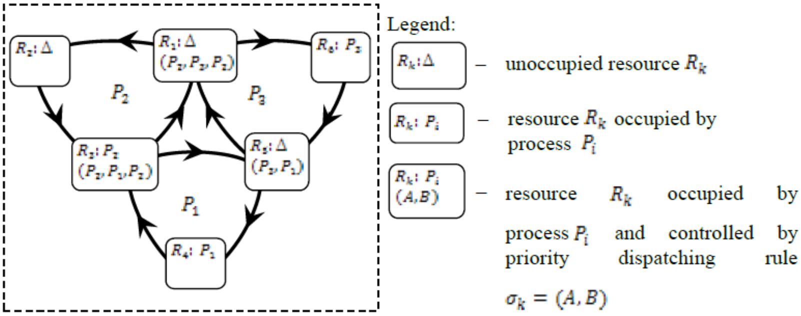

Fig. 3.8. System of concurrent cyclic processes

Systems of this type can be represented as Systems of Concurrent Cyclic Processes (SCCP) [4], see Fig. 3.8, where processes (P_1, P_2, P_3) are carried out according to assigned transportation routes, and the order in which processes acquire shared resources is determined by the priority dispatching rules σ_k. For instance, the order in which resource R_3 from Fig. 3.8 will be acquired is P_2, P_1, P_2 (and then, again, P_2, P_1, P_2). For such systems, we usually try to answer the following – is it possible to cyclically carry out these concurrent processes? If so, what are their time periods? The subsequent states of the system corresponding to this solution are presented in Fig. 3.9.

3.2. Problem Statement

Consider SCCP system shown in Fig. 3.10 composed of the set of resources $\{{}^{(i)}R_1, \ldots, {}^{(i)}R_{19}\}$ and four cyclic digraphs passing on by the following sequences of resources:

${}^{(i)}p_1 = ({}^{(i)}R_1, {}^{(i)}R_2, {}^{(i)}R_3, {}^{(i)}R_4, {}^{(i)}R_5, {}^{(i)}R_6)$,
${}^{(i)}p_2 = ({}^{(i)}R_3, {}^{(i)}R_7, {}^{(i)}R_8, {}^{(i)}R_9, {}^{(i)}R_{10}, {}^{(i)}R_{11})$,
${}^{(i)}p_3 = ({}^{(i)}R_4, {}^{(i)}R_{11}, {}^{(i)}R_{12}, {}^{(i)}R_{13}, {}^{(i)}R_{14}, {}^{(i)}R_{15})$,
${}^{(i)}p_4 = ({}^{(i)}R_{10}, {}^{(i)}R_{16}, {}^{(i)}R_{17}, {}^{(i)}R_{18}, {}^{(i)}R_{19}, {}^{(i)}R_{12})$.

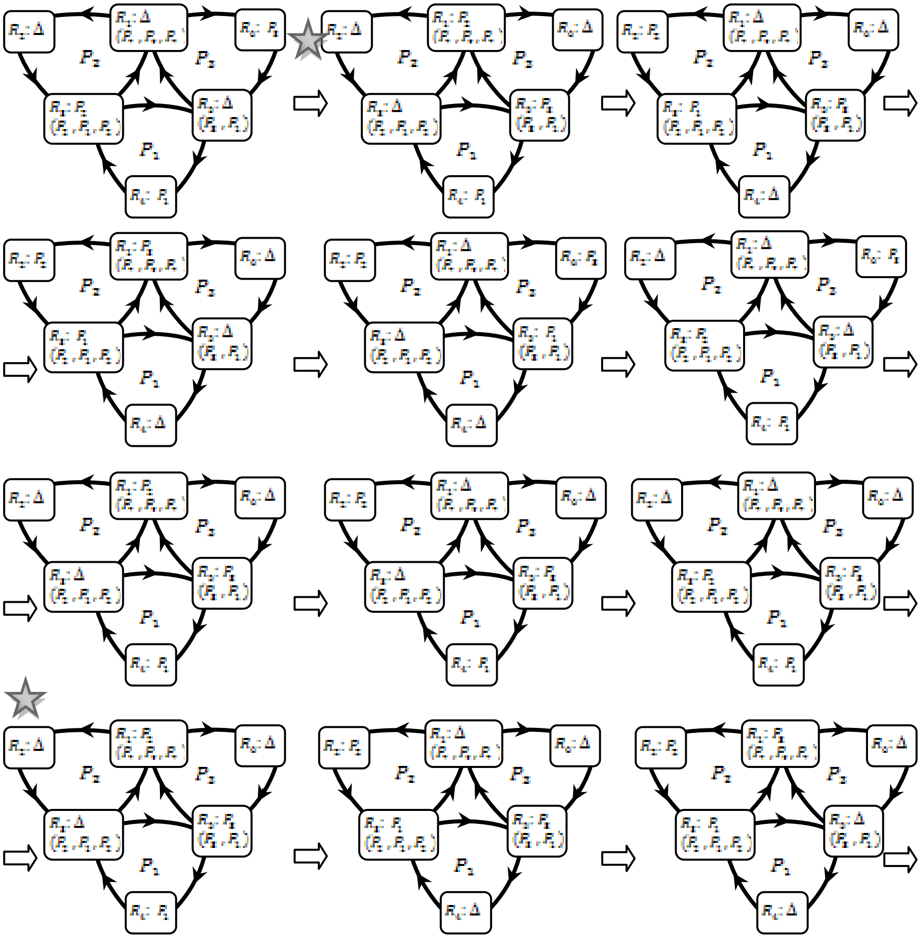

Fig. 3.9. Subsequent states of the SCCP from Fig. 3.8

Four cyclic processes ${}^{(i)}P_1$, ${}^{(i)}P_2$, ${}^{(i)}P_3$, ${}^{(i)}P_4$, are executed in this network along the guideways determined by sequences ${}^{(i)}p_1$, ${}^{(i)}p_2$, ${}^{(i)}p_3$, and ${}^{(i)}p_4$, respectively. The priority dispatching rules assigned to shared resources ${}^{(i)}R_3$, ${}^{(i)}R_4$, ${}^{(i)}R_{10}$, ${}^{(i)}R_{11}$, and ${}^{(i)}R_{12}$ are as follows: ${}^{(i)}\sigma_3 = \left({}^{(i)}P_2, {}^{(i)}P_1\right)$, ${}^{(i)}\sigma_4 = \left({}^{(i)}P_3, {}^{(i)}P_1\right)$, ${}^{(i)}\sigma_{10} = \left({}^{(i)}P_4, {}^{(i)}P_2\right)$, ${}^{(i)}\sigma_{11} = \left({}^{(i)}P_2, {}^{(i)}P_3\right)$, ${}^{(i)}\sigma_{12} = \left({}^{(i)}P_4, {}^{(i)}P_3\right)$.

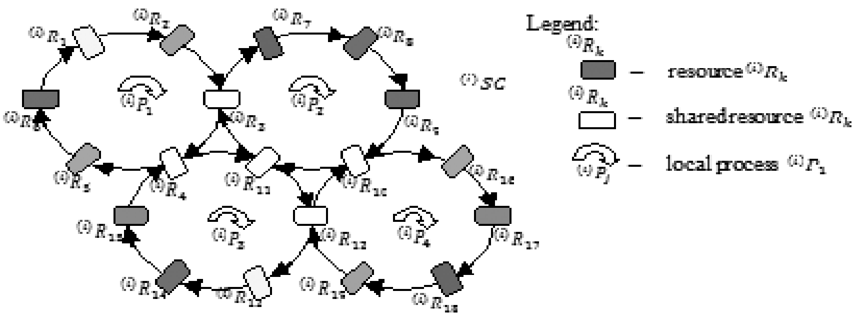

Fig. 3.10. The SCCP structure of a periodic structure object.

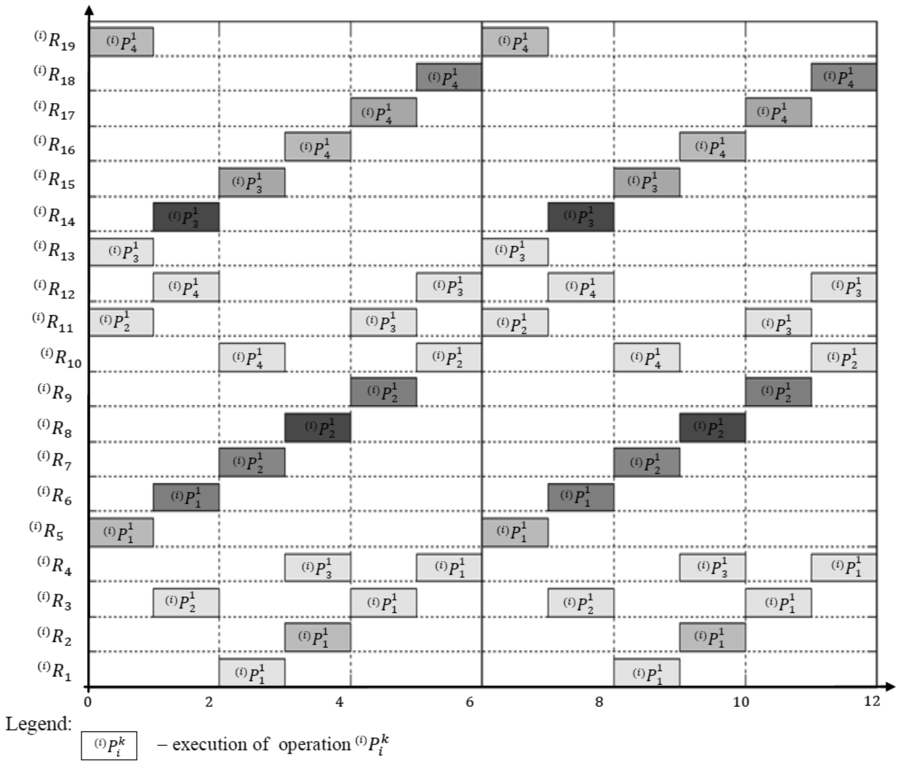

Fig. 3.11. The Gantt's chart of the SCCP from Fig. 3.10

The Gantt's chart of the processes cyclic execution is shown in Fig. 3.11. Since the all operation times are the same and equal to one unit of time (t.u. for short), the length of the cycle time is equal to 6.

Consider the periodic structure shown in Fig. 3.12 made of the basic object (structure) from Fig. 3.10. The response to the following question is sought: What is the cycle time of the periodic structure SCCP?

And then assuming the operation times are the same and equal to the one unit of time the following issues are consider:

- Assuming the arcs and vertices of cyclic digraphs from Fig. 3.9 correspond to transportation routes and sectors from Fig. 3.5., find out the shortest travel time between resources distinguished by ◎.
- Assuming a set of round trip itineraries find out corresponding to them travel times, i.e. the round trip cycles, and then find out the cycle of round trip itineraries.

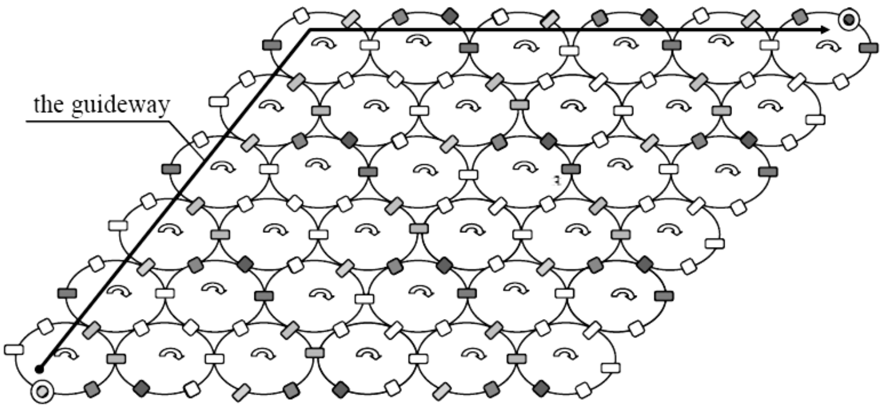

Fig. 3.12 An example of a periodic structure

3.3. Structural Periodicity Standing Behind System Periodic Behavior

Response to the above stated questions follow from the observation regarding the way the periodic structure shown in Fig. 3.12 is composed of a set of elementary objects (i.e. substructures shown in Fig. 3.10). The way the considered periodic structure is composed in the way as shown in Fig. 3.13.

In order to respond to the question: What is the cycle time of the periodic structure SCCP from Fig. 3.11? let us consider the Gantt's chart shown in Fig. 3.13 encompassing the behavior of SCCP composed of seven subsystems ${}^{(i)}SC$, ${}^{(i+1)}SC$,…, ${}^{(i+6)}SC$. The considered diagram can be seen as composition of the Gantt charts shape shown in Fig. 3.11 and following ${}^{(i)}SC$, ${}^{(i+1)}SC$,…, ${}^{(i+6)}SC$. That is easy to observe, that cycle time is equal to 6 t.u., i.e. to the cycle time of the elementary periodic structure from Fig. 3.10. Using the same argumentation, in general case it can be shown the cycle time of periodic structure SCCP from Fig. 3.12 is also equal to 6 t.u. That means, this modeling framework enables to evaluate the cyclic steady state of a given system of concurrent cyclic processes (SCCP). The questions arising concern of:

- an initial processes allocation guaranteeing the cyclic system behavior can be achieved under the given system's structure constraints, and
- a number of pipeline-like (serially flowing) local cyclic processes guaranteeing the cyclic system behavior can be achieved under the given system's structure constraints.

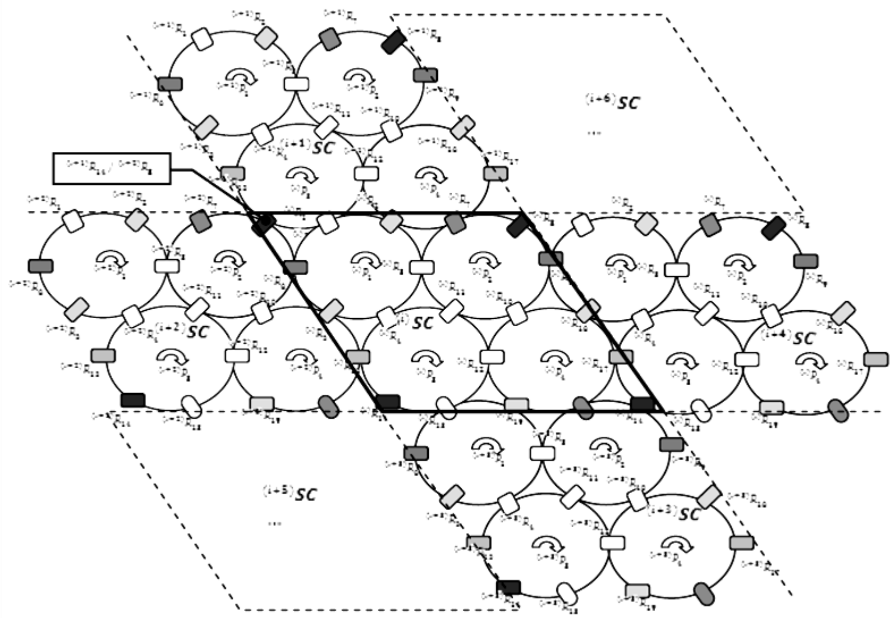

Fig. 3.13 The way the periodic structure is composed of elementary object from Fig. 3.10

Regarding the shortest travel time between resources distinguished by ◎, it can be easily calculated due to the formulae below.

$$Tt = \min_{\rho\in\Lambda}\left\{\sum_{t_i\in t(\rho)} t_i + \sum_{tp_i\in tp(\rho)} tp_j\right\} \tag{3.6}$$

where:

ρ – the guideway of the multimodal process linking resources distinguished by ◎, consists of operations required to travel between resources marked by ◎;

Λ – the set of all admissible guideways ρ;

t_i – the execution time of i-th operation from path ρ, $t(\rho) = \{t_1, \dots, t_i, \dots, t_g\}$ – the set of all execution times of operations belonging to guideway ρ;

tp_i – the awaiting time (covering suspension and transfer times) required to process change (e.g. metro lines etc.);

$tp(\rho) = \{tp_1, \dots, tp_i, \dots, tp_q\}$ – the set of all awaiting times from the guideway ρ.

The formulae follows from observation that that the itinerary considered can be seen as result of a multimodal process realization. The passenger's itinerary including different metro lines encompass a plan of multimodal process execution within a considered metro network can be seen as its example.

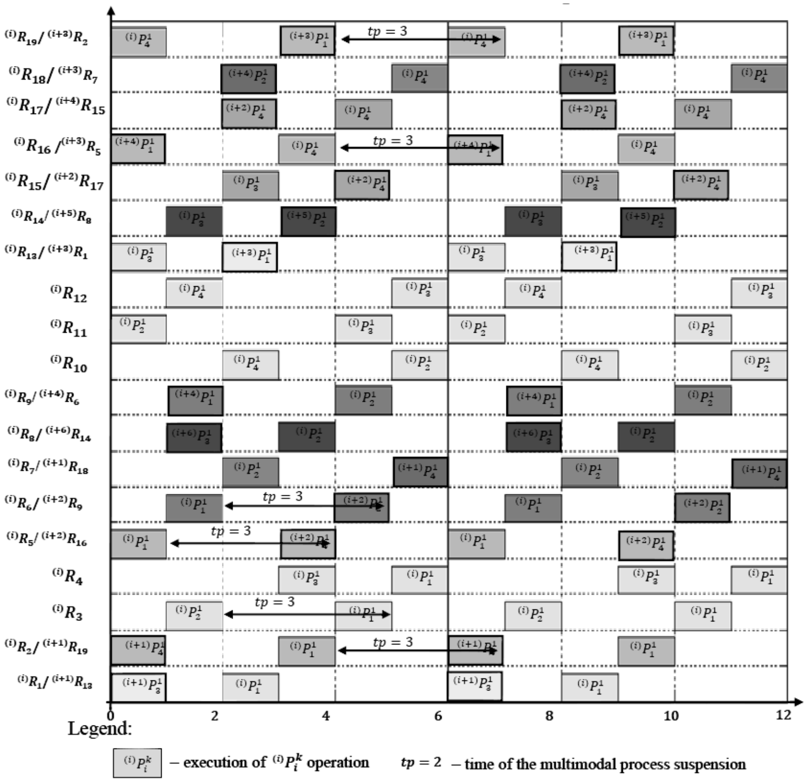

Fig. 3.14 The Gantt's chart of the SCCP composed of $^{(i)}SC, \ldots, {}^{(i+6)}SC$ as shown in Fig. 3.9

In turn the multimodal process can be seen as a process partially following local cyclic processes, i.e. encompassing local cyclic processes operations occurring along planned itinerary route. So, the travel time Tt between considered points in the periodic structure SCCP from Fig. 11 consists the sum of operations times calculated along the itinerary route as well as the sum of awaiting times caused by the multimodal process suspension at resources involved in switching from one local cyclic process to another. Note that the shortest travel between distinguished points is equal to $Tt = 34 + 30 = 64$ t.u and corresponds to the guideway from Fig. 3.12.

Regarding the set of round trip itineraries routes distinguished by bold: solid, dashed, doted, and dashed-dotted lines in Fig. 3.15, the corresponding travel cycles of round trips are calculated due to the formulae (4) and are equal to: $Tt_V = 56, Tt_G = 46, Tt_R = 40, Tt_B = 41$, respectively.

A new modeling framework enabling to evaluate the cyclic steady state of a given system of concurrent cyclic processes (SCCP). The following questions are of main interest: Does the assumed system behavior (e.g. cyclic steady states) can be achieved under the given system's structure constraints?

Consequently, the resultant cycle time of the round trip itineraries, calculated due to formulae (7) is equal to 264 040 t.u.:

$$T = LCM(Tt_R, Tt_G, Tt_B, Tt_V). \quad (3.7)$$

In general case, the operation times can be assumed as belonging to $\mathbb{N}^+$ as well as the shape and size of an elementary substructure can be different than shown in Fig. 3.10. Therefore, the considered periodic structure SCCP can be seen as homeomorphic model of many real life systems such like passengers' city transportation, and FMS's material handling networks. In this context, the approach presented leads to solutions allowing the traveler to reschedule his itinerary in case of unforeseen transportation network malfunction. Moreover, allows one to redesign, for instance an urban public transport system in such a way as to obtain its assumed robustness specified in terms of required (e.g. awaited by passengers) quantitative and qualitative behavioral (functional) features. So, the tools implementing this approach can support ex ante evaluation of spatial urban passengers/freight planning and spatial plans of urban public transport system.

Another interpretation of considered periodic structure SCCP assumes a given network of local cyclic acting AGV services. In such a regular network, i.e. composed of elementary and structurally isomorphic sub-networks, the workpieces pass their origin-destination routes among workstations using local AGVs. Since an AGVs fleet scheduling problem can be seen as a blocking job-shop NP-hard problem where jobs might block either workstations or AGVs, hence AGVs fleet scheduling in mesh-like environments also belongs to NP-hard problems. The solution sought assumes that schedules of locally acting AGVs match-up the given, i.e. already planned, schedules of workpieces machining.

Note, that since cyclic substructures generate cyclic behaviors, and since each local cyclic schedule match-up the cyclic schedule generated by assigned elementary structures, hence the behavior of the whole mesh-like structure is also cyclic. Moreover, since the cyclic behavior of the mesh-like structure can be easily evaluated from the behaviors of its component substructures, hence the size of searched states space [3,4,5] can be substantially reduced that results in shortening of AGVs fleet scheduling problem solution.

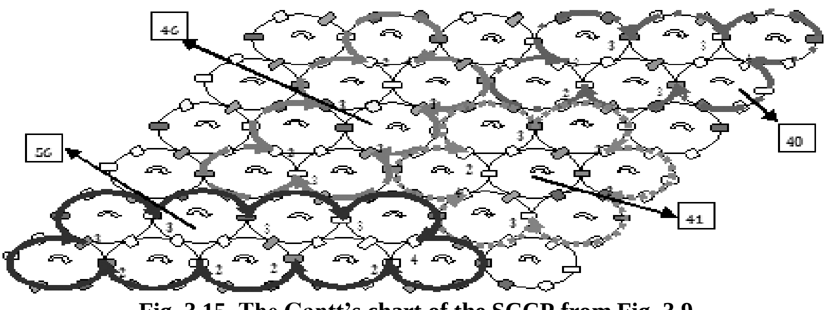

Fig. 3.15. The Gantt's chart of the SCCP from Fig. 3.9

3.4. Concluding Remarks

The paper introduces to the structural periodicity concept assuming a system structure is set-up of several isomorphic substructures. The structure considered can be seen as a digraph composed of a set of isomorphic sub-digraphs. Assuming vertices of each sub-digraph model the workstations and the arcs linking vertices model the material handling operations, the considered structure can be treated as graphical model of a mesh-like multimodal (i.e., composed of different means such as: automated guided vehicles, roller conveyors, tow lines, shuttle cars etc.) transportation network. In that context, workpiece flows are treated as multimodal processes passing through a mesh-like layout of FMS.

So, in opposite to traditional approach we assume the given network of local cyclic acting AGV services, i.e. corresponding to distinguished isomorphic sub-networks of FMS layout, where workpieces pass their origin-destination routes among workstations using local transportation means. The main objective is to provide conditions guaranteeing solvability of the cyclic processes scheduling, i.e. guaranteeing the right match-up of local cyclic acting AGV schedules to a given workpieces machining schedules.

In that context the goal of further work is to provide a declarative model enabling to state a constraint satisfaction problem aimed at multimodal transportation processes scheduling encompassing production flows.

References

[1] Abara J., Applying integer linear programming to the fleet assignment problem. In: Interfaces, 19, 1989, pp. 4-20.

[2] Banaszak Z., Bocewicz G., Decision Support Driven Models and Algorithms of Artificial Intelligence, Management Sciences Series, Warsaw University of Technology, Faculty of Management, 2011, 237 p.

[3] Bocewicz G., Banaszak Z., Declarative approach to cyclic scheduling of multimodal processes. In: EcoProduction and Logistics, Golińska P., (Eds.), Vol. 1, Springer-Verlag, Berlin-Heidelberg, 2013, Vol. 1, Springer Heidelberg, 2013, pp. 203-238.

[4] Bocewicz G., Banaszak Z., Declarative approach to cyclic steady states space refinement: periodic processes scheduling. In: International Journal of Advanced Manufacturing Technology, SI: Advanced Dispatching Rules for Large-scale Manufacturing Systems, DOI 10.1007/s00170-013-4760-0.

[5] Bocewicz G., Wójcik R., Banaszak Z., Cyclic Steady State Refinement. In: International Symposium on Distributed Computing and Artificial Intelligence, series: Advances in Intelligent and Soft Computing, Abraham A., Corchado J.M., Rodríguez González S., de Paz Santana J.F. (Eds.), Vol. 91, Springer-Verlag, Berlin Heidelberg, 2011, pp. 191-198.

[6] Boyle D. K. Fixed-Route Transit Ridership Forecasting and Service Planning Methods.Transportation Research Board National Academies. WASHINGTON, D.C., 2006.

[7] Deris S., Omatu S., Ohta H., Kutar L.C.S., Samat P.A., Ship maintenance scheduling by genetic algorithm and constraint-based reasoning. In: European Journal of Operational Research, 112, 1999, pp. 489-502.

[8] Levner E., Kats V., Alcaide D., Pablo L, Cheng T.C.E, Complexity of cyclic scheduling problems: A state-of-the-art survey. In: Computers &Industrial Engineering, Vol. 59, Issue 2, 2010, pp. 352-361.

[9] Maldovan M., Thomas E., Periodic Materials and Interference Lithography, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2008.

[10] Polak M., Majdzik P., Banaszak Z., Wójcik R., The performance evaluation tool for automated prototyping of concurrent cyclic processes. In: Fundamenta Informatice. Vol. 60, No.1-4, 2004, pp. 269-289.

[11] Slowik A., Application of an Adaptive Differential Evolution Algorithm with Multiple Trial Vectors to Artificial Neural Networks Training. In: IEEE Transactions on Industrial Electronics, Vol. 58, Issue 8, 2011, pp. 3160-3167.

[12] Song J.-S., Lee T.E., Petri net modeling and scheduling for cyclic job shops with blocking. In: Computers & Industrial Engineering,Vol.34, No.2, 1998, pp. 281-295.

[13] Von Kampmeyer T., Cyclic scheduling problems, Ph.D. Dissertation, Fachbereich Mathematik/Informatik, Universität Osnabrück, 2006.

STRUCTURAL AND BEHAVIOURAL SYSTEM PERIODICITY

Abstract: The theoretical prediction of the behavioral properties of periodic structures is less difficult than in the case of nonperiodic ones. That is because all the information needed to describe the entire structure is given by the elementary substructure itself and by the manner it repeats in the whole periodic structure. So, only a small portion of the structure (which includes the repeating substructure) needs to be considered to obtain the properties of the whole periodic structure. In that context, the contribution provides the discussion of some system periodicity issues, and is aimed at modeling and evaluation of relationships linking the system structure features with required system's functioning.

Key words: Structural periodicity, behavioral periodicity, Diophantine problem, cyclic scheduling, multimodal processes

STRUKTURALNA I FUNKCJONALNA PERIODYCZNOŚĆ SYSTEMU

Streszczenie: Jednym z czynników decydujących o zachowaniu systemu jest jego struktura. Ponieważ w ogólnym przypadku, funkcje łączące parametry struktury systemu z parametrami jego zachowania mają nieliniowy charakter, łatwo zauważyć, że złożoność problemu prognozowania parametrów funkcjonowania w systemach o strukturze regularnej jest mniejsza niż ma to miejsce w przypadku struktur nieregularnych. Oznacza to możliwość wyznaczenia związków pozwalających na przenoszenie cech strukturalnych elementarnych obiektów struktury regularnej (a zatem i wynikających z nich lokalnych zachowań) na strukturę systemu i związane z nią jego zachowanie. W przedstawionym kontekście, przedmiot niniejszej pracy obejmuje analizę wybranej (charakteryzujących się regularną strukturą) klasy modeli SCCP. Uzyskane wyniki obejmują warunki konieczne cyklicznych zachowań tej klasy systemów oraz realizowanych w nich systemów procesów multimodalnych.

Słowa Kluczowe: periodyczność strukturalna, periodyczność funkcjonalna, problem diofantyczny, harmonogram cykliczny, proces multimodalny

*HENRYK CZARNECKI**

4. The software application for the analysis of interpolation errors in concave and convex surface machining

Introduction

The development of microelectronics, microprocessor techniques and computerized systems used for machine tool control and monitoring has a significant impact on the design and operational capabilities of contemporary machine tools. These enable increasingly complex machines to be built, which often have the form of machining centres performing multiple engineering tasks (such as turning and milling, etc.). The advisability of implementing automation, including computer-controlled machines, is generally determined by economic considerations, though other reasons are also possible, such as productivity maximization, competitive struggle to survive in the market, etc. In each case, automation is aimed at reducing internal production costs, increasing productivity, reducing labour consumption, reducing working arduousness, etc.

The purpose of a machine tool's control system is to execute the drives' motions in the controlled axes by processing numerical data containing information on the working program. The machining program has preset geometrical and engineering & operational data. The geometrical data contained in the program are the characteristic points of the workpiece contour, while the numerical control system in the interpolator defines the servo-drive control quantities as a relationship of path versus time. So, it can be said that it determined the intermediate points of the tool's position on the preset path. During machining, the characteristic (setting) point of the tool shaping the surface being machined should move along the path set in the drawing, which can be divided into straight or curvilinear segments. The motions in individual axes should be synchronized, and the determination of the intermediate points by the interpolator takes place in accordance with the rules resulting from the type of interpolation. The interpolator generates data for each axis separately [1,2,3].

Developing a part machining program for a numerically controlled machine tool includes calculation of the increments in the path of the tool moving along the generating line of the contour being machined. The coordinates of the point from which the technologist starts calculating the increments are base coordinate for a given tool, as measured in parallel to the machine tool's guides. For turning lathes, the coordinate along the "Z" axis is normally defined as the distance of the tool's characteristic point from the machined part surface contacting the chuck, while the

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"X" coordinate, as the distance of the characteristic point from the machine tool axis. From the machine tool's base point, the tool is guided along the paths either parallel or skew to the machine tool guides; this is true for both idle (fast) and working movements in machining of cylindrical or conical surfaces. The calculation of the increments for these cases does not face any difficulties; however, the situation is different when machining arcs. The path considered by us is the path of the tool's characteristic point, which is consistent with the contour of the machined bed only in the case, where the cutting tool tip rounding radius is equal to zero. Whereas, in the case where the cutting tool tip rounding radius is other than zero, which is the case in practice, the path along which the characteristic point moves does not coincide with the machined arc circle.

4.1. Theoretical analysis of interpolation errors

Due to the rounding of the cutting tool tip, its actual machining point changes during machining. With tool movements not parallel to the "Z" or "X" axis, the forming contour does not coincide with the contour defined in the program, as illustrated in Figure 4.1.

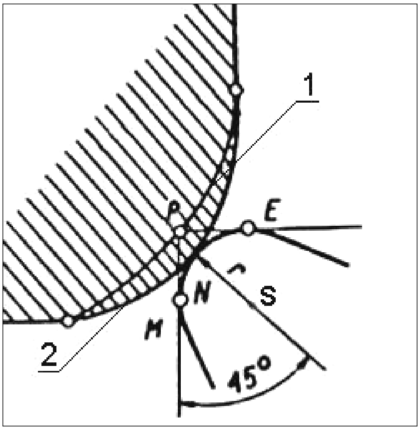

Fig. 4.1. Turning of a contour segment out-of-parallel to the machine tool axis (circular arc): 1 – preset contour, 2 – obtained contour [1]

We can see that a new contour forms at that time, which can be described by the parametric equations presented later on in this paper. The contour preset in the program differs from the actual one by an error (deviation), whose value changes with the change in the tool clearance angle and cutting plate positioning in the tool. The maximum value of this deviation will be for an angle approximate to 45°.

Curvilinear surfaces most commonly found in workshop practice are any types of inner, outer, concave and convex radii and arcs. The task was examined on the example of turning, on the assumption that the calculation comes down to determining the coordinates of the cutting tool's characteristic point "P" at any arbitrary position relative to the base surfaces of the workpiece. The position of point "P" is defined on the machine tool axes by the "Z" and "X" coordinates. The "Z" coordinate consists of a constant quantity "L" defining the distance of the arc origin from the base along the "Z" axis, and a variable that changes as the cutting tool moves. The "X" coordinate includes the difference between the radius origin diameter and the variable changing with the cutting tool movement.

Establishing the mathematical relationship for obtaining the coordinates of the intermediate points of the tool path boils down to determining the successive cutting tool positions during radius machining. This comes down to defining the trajectory relative to the base surfaces of the workpiece.

4.1.1. Making the outer arc

The outer arc can have either a convex or concave shape, as illustrated in Figure 4.2. Its machining may proceed from the major diameter towards the workpiece centre, or vice versa, that is from the centre towards the major diameter.

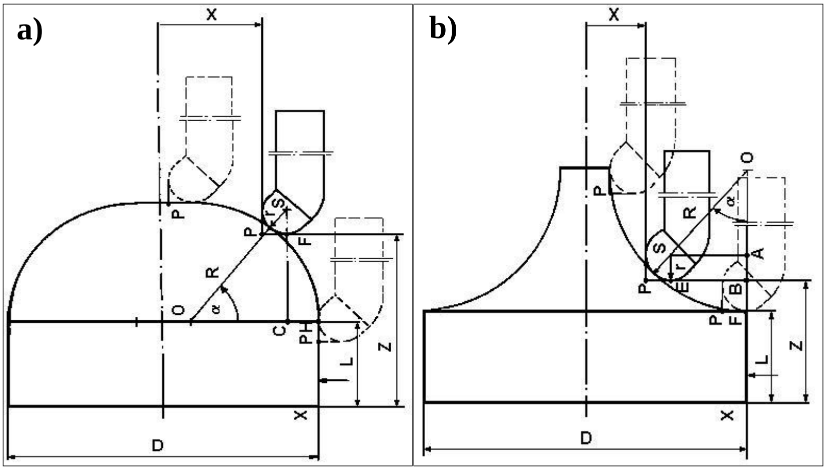

Fig. 4.2. Schematic of machining the arc of the outer surface, a – convex, b – concave

4.1.2. Making the inner arc

The inner arc may also be either convex or concave, as illustrated in Figure 4.3, and can be executed by the tool moving from the major diameter to the minor diameter, or vice versa.

The schemes presented above were used for deriving the equations for the trajectory of the characteristic point "P" for particular cases. The relationships obtained from the theoretical discussions are summarized in Table 4.1.

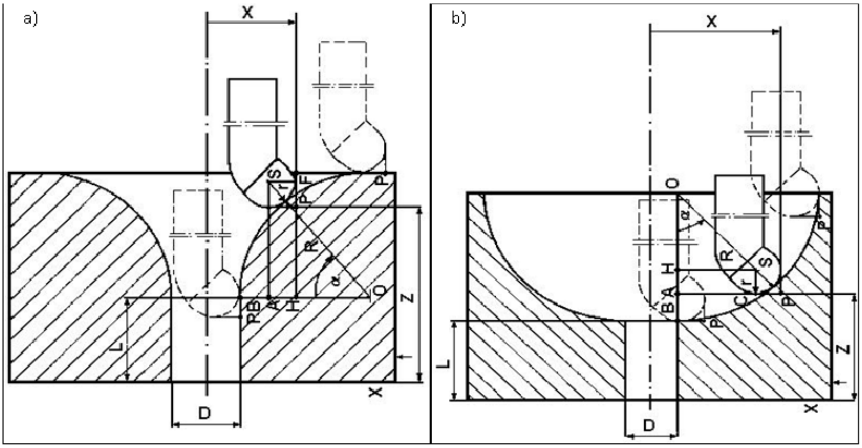

Fig. 4.3. Schematic of machining the arc of the inner surface, a – convex, b – concave

Tab. 4.1. A summary of relationships defining the trajectory of the tool's characteristic point

Arc type		Equation for the trajectory of the characteristic point (P) with movements	
		from the major diameter to the minor diameter	from the minor diameter to the major diameter
outer	convex	Z = L + (R + r)sinα - r X = D – 2(R + r)(1 – cosα)	Z = L - (R + r) (1 – cosα) X = D + 2(R + r)sinα
	concave	Z = L + (R – r)(1 – cosα) X = D – 2 [(R – r)sinα+ r]	Z = L + (R – r)(1 – sinα) X = D – 2(R – r)cosα
inner	convex	Z = L + (R + r)sinα - r X = D + 2(R + r)(1 – cosα)	Z = L – (R + r)(1 – cosα) X = D – 2(R + r) sinα
	concave	Z = L + (R – r)(1 – cosα) X = D + 2 [r+ (R – r)sinα]	Z = L + (R – r)(1 – sinα) X = D + 2(R – r)cosα

The obtained relationships were utilized for developing a software application to be used for simulating the cutting process in machining arcs using a tool with a corner rounding radius, calculating the errors of the obtained contour, and determining the new cutting tool tip path to obtain the actual contour consistent with the programmed one.

4.2. The software application for the analysis of interpolation errors

As the programming tool for writing the interpolation error analyzing program, the Delphi 5 object-oriented programming language was used. This is a Rapid Application Development tool for creating applications in the Windows environment. It has three basic features: ease of operation; a fast, functional compiler and an efficient output code; and an integrated, scalable database access mechanism [4,5].

4.2.1 Structure of the program

The developed software program for the analysis of the error of interpolation of concave and convex surfaces consists of eight forms, as shown schematically in Figure 3.4, and thus also eight corresponding code segments. The most developed and most important part of the program is the fragment with the main form ***Analysis***, which makes use of the presented equations and computational procedures for calculation.

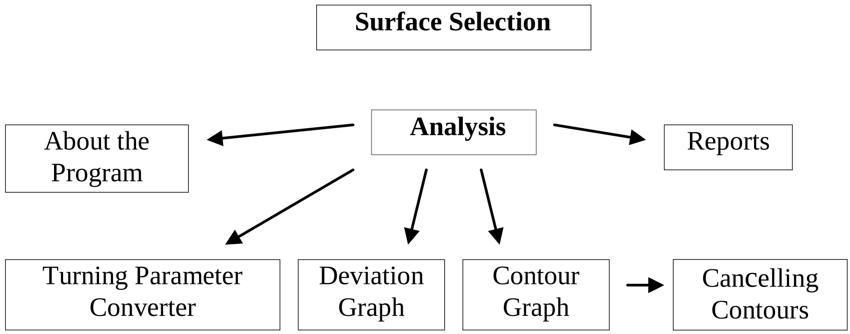

Fig. 4.4 . Software program's forms

The purpose of respective functional modules is as follows:

– The *Surface Selection* module enables the selection of the type of surface that we want to subject to interpolation error analysis, i.e. the outer arc, either convex or concave; or the inner arc, either convex or concave

– The *Analysis* module – is the application's main (computational) module. It includes all the main formulae and relationships necessary for the calculation of the linear and circular interpolation errors. After making the calculation, we are able to use the remaining modules which are designed for the *simulation and visualization* of the results.

– The *Turning Parameter (Dimension) Converter* module performs the calculation of the dimensions of coordinate (D and L) positioning for the varying machining direction.

– The *Deviation Graph* module enables the graphical presentation of the contour deviation within the full machining angle range.

– The *Contour Graph* module executes the graphical simulation of the contour outline of the outer convex or concave arc, or the inner convex or concave arc being machined.

– The *Report* module enables all results of calculations performed within the program to be summarized, with the option of their recording or printing.

– The operation of the program involves declaring data, which are entered in declaration spaces in respective forms windows. After confirming and making calculations, we can proceed with the next tasks to be executed in a selected module.

After running the „Interpolator 2002"program, a form shows up in the *"Select Surface Type"* window, see Figure 4.5. We declare the type of contour outline of the outer convex or concave arc, or the inner convex or concave arc to be machined.

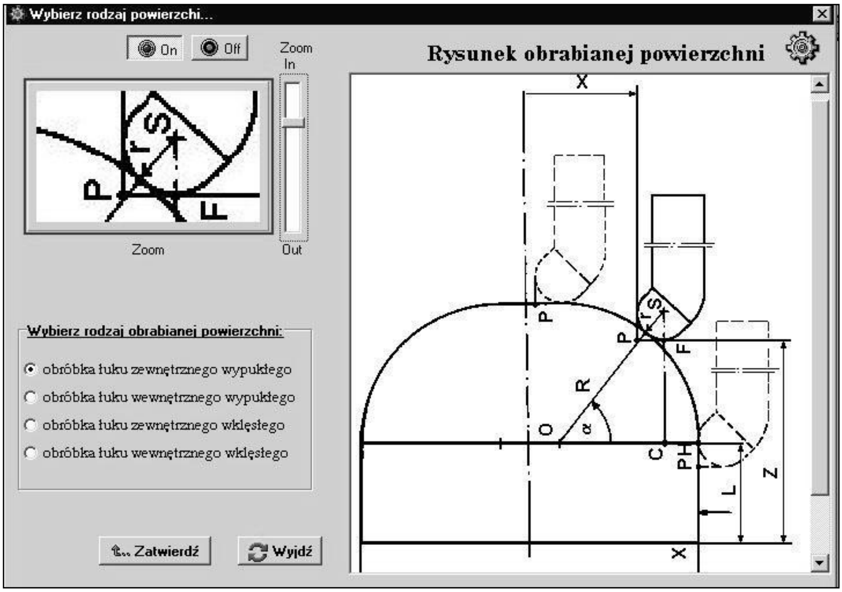

Fig. 4.5. The "Select Surface Type" form view

In addition, this form has the capability to visualize the selected surface in the review window using either the vertical scrolling bar or the Magnifying Glass tool (marked with the red frame in the figure), with which we can magnify a selected fragment of the drawing, e.g. the cutting tool tip.

The Magnifying Glass tool is operated with two buttons, On and Off, and the bar adjusting the magnification of the drawing fragment, Zoom Out / In.

Interpolation error analysis

After selecting and confirming the type of surface to be machined, the *Interpolation Error Analysis* form opens up, see Fig. 4.6. This is the main window of the program, in which we declare data for the complete analysis of linear or circular surface interpolation errors. After declaring and confirming the data, the program will perform analysis and determine the values of respective errors.

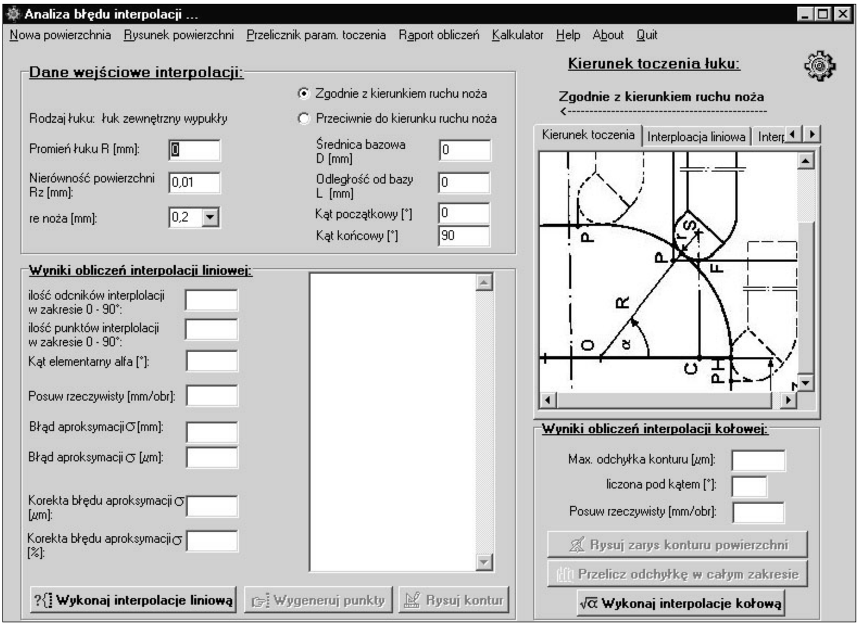

Fig. 4.6. The program's Main Window view

As can be seen in Figure 4.6, the Main Window is split into two specific parts, i.e. the left-hand part – for linear interpolation calculation, and the right-hand part – for circular interpolation calculation. The input data for the analysis of both the former and the latter interpolation are identical, namely: R – arc radius [mm]; surface roughness height – Rz, which is tantamount to our assumed arc approximation error; re – cutting tool rounding radius [mm] (it is recommended to use the one already defined in the program). Moreover, the turning direction – either consistent with the drawing, or not; the starting diameter, D [mm] and the distance from the base, L [mm]; and the starting and final angles of the arc to be made [°] should also be declared. After entering and confirming the data or, if entered erroneously, correcting the declaration, the calculation follows. For circular interpolation analysis, the coordinates of the interpolation segment ends are generated. The calculation is executed in two stages, namely: the calculation of the maximum contour deviation and the calculation of the deviation in the full turning angle range. A view of the declaration & calculation window is shown in Figure 4.7.

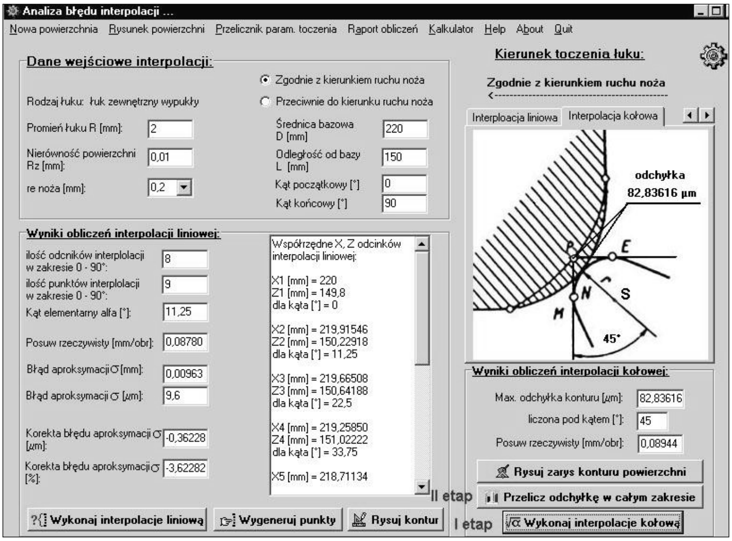

Fig. 4.7. A view of the form after the Circular Analysis has been made

The figure also illustrates the results, if the arc making task were executed using linear interpolation (the left-hand part of the window – denoted as Stage II). If, on the other hand, the *Convert the deviation in the whole range* task is run, we will obtain the graph as shown in Figure 4.8.

If, on the other hand, *Contour Outline Graph* is selected, the form as shown in Fig. 4.9 will show up.

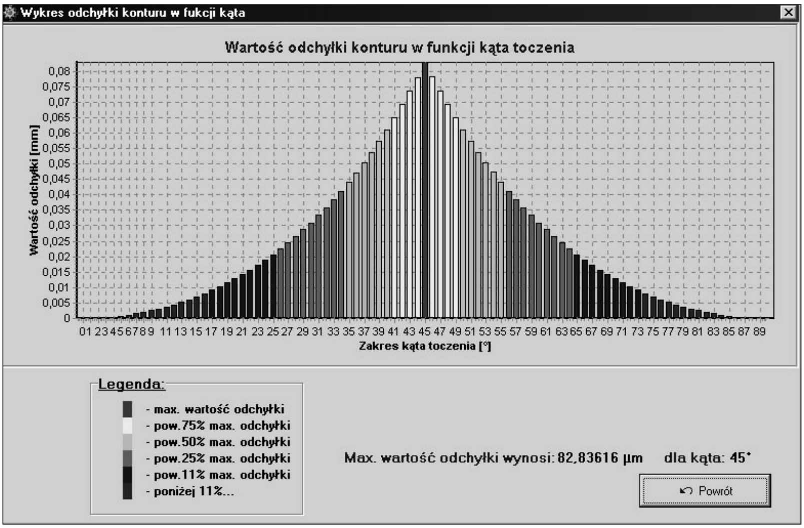

Fig. 4.8. A view of the "Graph of contour deviation as a function of angle" form

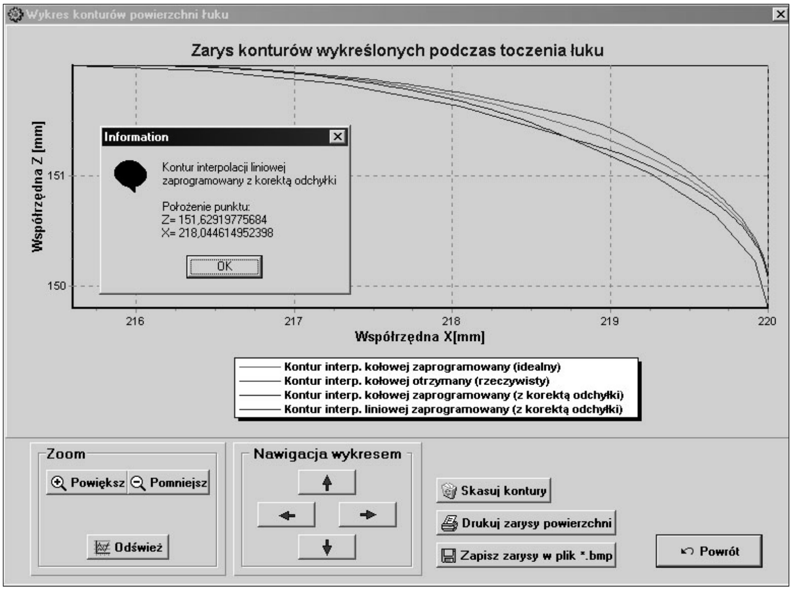

Fig. 4.9. A view of the "Graph of arc surface contours" form

Additionally, on this form, we can determine the coordinates of an indicated point in the graph by using the *On Click* (*mouse click*) function that identifies the contour point. Indicating a selected point in the curve with the cursor results in the determination of its coordinates, as illustrated in Fig. 4.9.

When the curvature contour machining direction is changed, it will be necessary to convert the D diameter and L length dimensions. Therefore, a tab is provided in the program, which enables this function, as shown in the window in Figure 4.10.

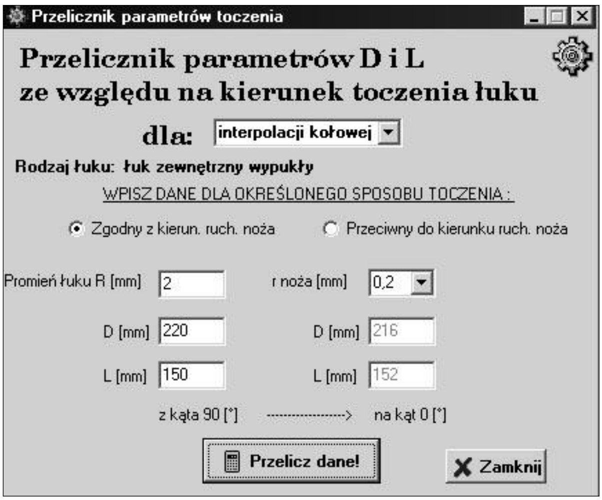

Fig. 4.10. A view of the "Turning parameter converter" form

This form enables the quick conversion of the initial basic parameters, D – turning diameter and L – distance from the base.

The conversion is necessary, if we want to make interpolation in the reverse turning direction (i.e. we change over the angles - the angle of 0 degrees in the opposite direction is 90 degrees, and vice versa).

In the form, we declare the type of interpolation (linear or circular) and the machining direction, either consistent or inconsistent with the drawing in the *Analysis* form, and then enter the data (D, L and the radii T and re).

By pressing on the *Convert Data* button, we obtain the values of the parameters for turning in the opposite direction.

The gear icon  visible in the upper right-hand corner of each form enables quick access to the Help file. Clicking on this icon opens the Help file of the Interpolator 2002 program.

Conclusions

The presented „Interpolator 2002" software application enables planning, converting and analyzing errors that occur in the machining of concave or convex surfaces in instances, where our cutting tool has a rounding radius. The determined relationships and the calculations carried out using the *Interpolation Error Analysis* program are of theoretical value and make it possible to formulate numerous practical recommendations related to the selection of optimal parameters before proceeding with the machining of concave or convex surfaces. In such optimization, expected errors of interpolation, both linear and related to the arc of the machined surface, need to be allowed for.

Owing to the „Interpolator 2002" software, we will know their values and be able to simulate the machining by program - by selecting the optimal values of the starting parameters, and primarily of r_e (the cutting tool rounding radius) so that these errors be as small as possible. We are also able to change the radius value declared in the program so as to obtain the actual radius conforming to the technical documentation. The application has also educational values when used in teaching the rules of programming.

References:

[1] Kosmol J.: Automatyzacja obrabiarek i obróbki skrawaniem. WNT, Warszawa, 1995.
[2] Honczarenko J.: Elastyczna automatyzacja wytwarzania, obrabiarki i systemy obróbkowe. WNT. Warszawa 2008.
[3] Stach B.: Podstawy programowania obrabiarek sterowanych numerycznie. WSiP Warszawa 1999.
[4] Teixeira S., Pacheco X.: Delphi 4 Vademecum profesjonalisty. Tom 1 i 2, Wyd. Helion. Gliwice, 1999 r.
[5] Marco Cantu M.: Delphi 4. Praktyka programowania. Wyd. Mikom. Warszawa, 1999 r.

THE SOFTWARE PROGRAM FOR ANALYSIS OF INTERPOLATION ERRORS IN CONCAVE AND CONVEX SURFACE MACHINING

Abstract: The paper discusses the problems of interpolation in the machining of concave and convex surface on the example of turning. Assumptions for the calculation of the trajectory of the real outer and inner arcs in machining using a tool with a corner rounding radius have been presented. The results of theoretical discussions are summarized in a table. The derived parametric equations have been used for developing a software application written in the Delphi object-oriented programming language. The successive views of the forms enable one to make calculations and their presentations both in a numerical and graphical forms.

Keywords: interpolation errors, calculation program

SYSTEM KOMPUTEROWY DO ANALIZY BŁĘDÓW INTERPOLACJI PRZY OBRÓBCE POWIERZCHNI WKLĘSŁYCH I WYPUKŁYCH

Streszczenie: W opracowaniu omówiono zagadnienia interpolacji przy obróbce powierzchni wklęsłych i wypukłych na przykładzie toczenia. Przedstawiono założenia do obliczeń trajektorii rzeczywistego łuku zewnętrznego i wewnętrznego przy obróbce narzędziem z promieniem zaokrąglenia naroża. Wyniki rozważań teoretycznych zestawiono w tablicy. Uzyskane równania parametryczne posłużyły do opracowania programu komputerowego napisanego w języku programowania obiektowego Delphi. Kolejne odsłony formularzy pozwalają na dokonanie obliczeń i ich prezentacje zarówno liczbową jak graficzną.

Słowa kluczowe: błędy interpolacji, pogram obliczeniowy

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ŁUKASZ SOBASZEK[**]

5. Simulation of production flow using MATLAB system

Introduction

Complexity of production processes and production flow causes that there is requirement for methods and tools which helps in the process of manufacturing processes optimization [4,5]. Because of that, the tool which is widespread in the area of production engineering are computer simulations. Simulation, in general sense, is the imitation of the operation of a real-world process or system over time. The act of simulating something first requires that a model be developed; this model represents the key characteristics or behaviors of the selected physical or abstract system or process. The model represents the system itself, whereas the simulation represents the operation of the system over time [1].

On the market there are some computer systems which allow to simulate production processes. These are for example Enterprise Dynamics [12], Flexim [13], Arena [14]. Simulation methods can be used to analyzing and optimization the current and future behaviour of production systems or infrastructure.

This article presents possibility of using the Matlab system for the purpose of production flow analyzing. In particular, there are presented main features of Matlab system and its ability to simulate discrete manufacturing processes on the example of two machine-tools production lines. The main steps of modelling, simulating and analyzing output data from simulation process are also shown in following chapters.

5.1. Characteristics of MATLAB system

MATLAB is a high-performance language for technical computing [11]. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include:

- math and computation,
- algorithm development,
- modeling, simulation, and prototyping,
- data analysis, exploration, and visualization,
- scientific and engineering graphics,

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– application development, including Graphical User Interface building [9].

MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows you to solve many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar non-interactive language such as C or Fortran.

The name MATLAB stands for matrix laboratory. MATLAB was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects, which together represent the state-of-the-art in software for matrix computation.

MATLAB has evolved over a period of years with input from many users. In university environments, it is the standard instructional tool for introductory and advanced courses in mathematics, engineering, and science. In industry, MATLAB is the tool of choice for high-productivity research, development, and analysis.

MATLAB features a family of application-specific solutions called toolboxes. Very important to most users of MATLAB, toolboxes allow you to *learn* and *apply* specialized technology. Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. Areas in which toolboxes are available include signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and many others.

The MATLAB system consists of five main parts [7]:

- *The MATLAB language* – This is a high-level matrix/array language with control flow statements, functions, data structures, input/output, and object-oriented programming features. It allows both "programming in the small" to rapidly create quick and dirty throw-away programs, and "programming in the large" to create complete large and complex application programs.
- *The MATLAB working environment* – This is the set of tools and facilities that you work with as the MATLAB user or programmer. It includes facilities for managing the variables in your workspace and importing and exporting data. It also includes tools for developing, managing, debugging, and profiling M-files, MATLAB's applications.
- *Handle Graphics* – This is the MATLAB graphics system. It includes high-level commands for two-dimensional and three-dimensional data visualization, image processing, animation, and presentation graphics. It also includes low-level commands that allow you to fully customize the appearance of graphics as well as to build complete Graphical User Interfaces on your MATLAB applications.
- *The MATLAB mathematical function library* - This is a vast collection of computational algorithms ranging from elementary functions like sum, sine,

cosine, and complex arithmetic, to more sophisticated functions like matrix inverse, matrix eigenvalues, Bessel functions, and fast Fourier transforms.

- The MATLAB Application Program Interface (API) - *This is a library that allows you to write C and Fortran programs that interact with MATLAB. It include facilities for calling routines from MATLAB (dynamic linking), calling MATLAB as a computational engine, and for reading and writing MAT-files.*

Generally, the performance characteristics of a model intended for a simulation study can be developed with the Matlab SimEvent software. A model workflow is presented in fig. 5.1. Mathematical model classifications usually includes deterministic models (input and output variables are fixed values) or stochastic models (at least one of the input or output variables is probabilistic); static models (time is not taken into account) or dynamic models (time-varying interactions among variables are taken into account) [3].

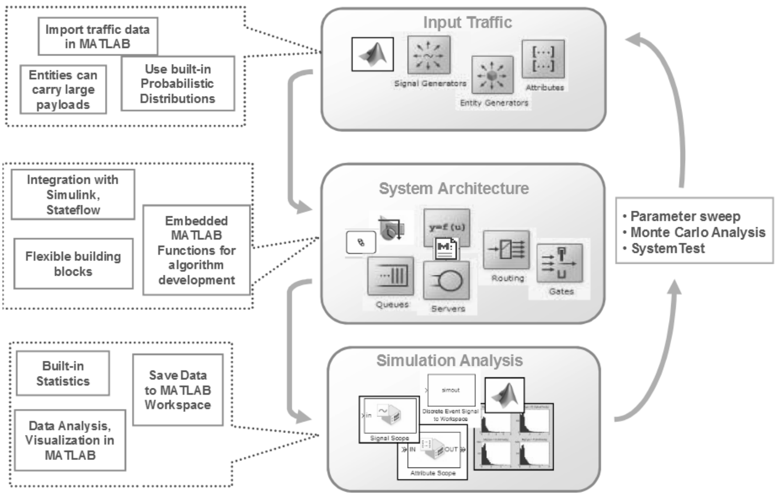

Fig. 5.1. SimEvents key features [10]

5.2. SimEvents – Matlab's tool for simulation

SimEvents is a discrete event simulation tool developed by MathWorks and it is embedded in Simulink [15]. It adds a library of graphical building blocks for modeling queuing systems to the Simuling environment. It also adds an event-based simulation engine to the time-based simulation engine in Simulink [2]. It allows to model event-driven communication between components to analyze and optimize end-to-end latencies, throughput, packet loss, and other performance characteristics.

SimEvents provides a block library that enables to create, process, store, and move entities in a system. The main library contains predefined blocks such as:

1. *Generators* – blocks which generate entities, or function calls (i.e., events that call Simulink blocks), or random varieties;
2. *Queues* – blocks where entities can be temporarily stored while waiting to access a resource;
3. *Servers* – blocks that model various types of resources;
4. *Routing* – blocks that control the flow of entities by enabling/disabling access queues and servers;
5. *Gates* – blocks that control the flow of entities by enabling/disabling access of entitles to certain blocks;
6. *Event Translaction* – blocks that enable communication between SemEvents and Simulink by translanting events into function calls.
7. *Attributes* – blocks that assign and modify data to entities. Various control actions are then made based on the values of these data, allowing blocks to differentiate between entities they process;
8. *Subsystems* – these allow a combination of blocks to be executed upon occurrence of specific events (not upon Simulink sample times);
9. *Timers and Counters* – blocks that measure event occurrence times or time elapsing between events and blocks that count occurrences of particular event types. These data are supplied to standard display or scope blocks in Simulink or specialized scopes designed specifically for SimEvents (fig. 5.2) [15].

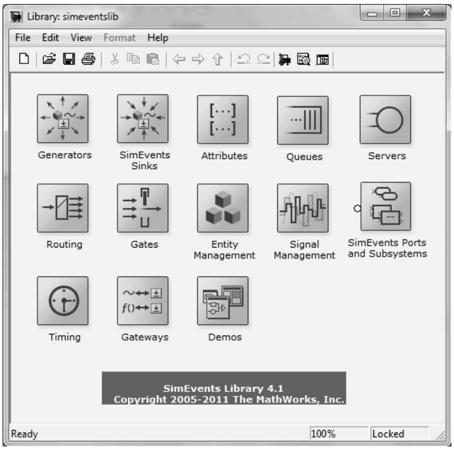

Fig. 5.2. SimEvents block libraries for building discrete-event simulations

It is possible to model both simple and complex networks of queues and servers. Establish paths on which entities travel in response to events is realized by connecting gate and switching blocks. These paths can include delays and selective switching criteria. Many parameters within SimEvents can be statistically determined to model probabilistic variations in the system. It is also possible to build own domain-specific library blocks by using key Simulink capabilities, such as masking subsystems and creating libraries, and adding special SimEvents signal ports to Simulink subsystems that produce and consume events [8].

In SimEvents, communication across blocks is based both on signals and entities – what enables to simulate manufacturing discrete processes. The “entity” concept is motivated from the view of a DES an environment consisting of “users” and “resources”: users request resources for a certain amount of time, and then relinquish them so that other users may access them. Examples of users, when modeling production systems, are parts in a manufacturing system. Examples of resources are machines in a factory.

5.3. Building of simulation models in MATLAB SimEvents

To build a model of production flow in Matlab SimEvents it is necessary to open New Model Window (Menu: File=>New=>Model) and open SimEvents Libraries. The main SimEvents library (fig. 5.1) can be opened by entering “simeventslib” command in the Matlab Command Window.

Building the model of the process/system is realized by moving proper blocks from libraries into the model window. Double-click of the block in the library causes opening blocks sublibrary – where it is possible to find proper block. The example of process of choosing the Time-Based Entity Generator block was shown in Fig. 5.3.

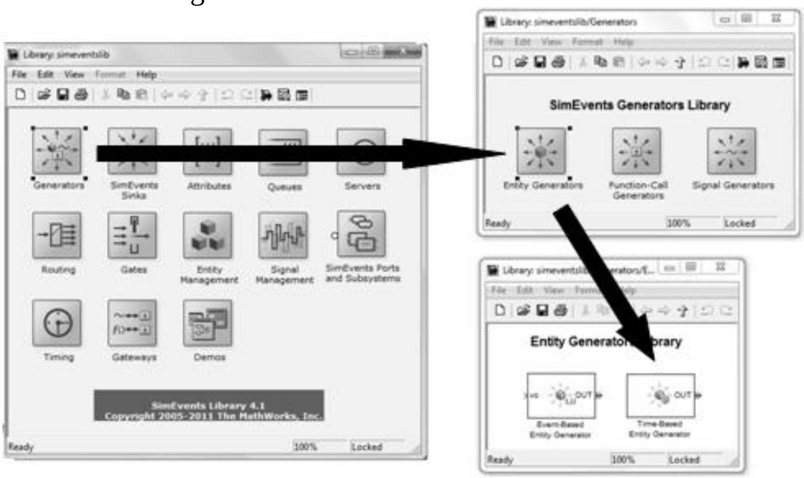

Fig. 5.3. Following steps of Time-Based Entity Generator choosing

As a result, the example model window looks like the figure shown in Fig. 4.4. The model presents two-machine-tools manufacturing line and it contains blocks that represent the key processes in the simulation: block that generate entities (*Processed parts generator*), store entities in a queue (*Machine-tool store A*, *Machine-tool store B, Store of processed parts*), serve entities (*Machine-tool A, Machine-tool B*) and create a plot showing relevant data

(*Signal scope 0, Signal scope A, Signal Scope B, Signal Scope Store 1, Signal Scope store 2*).

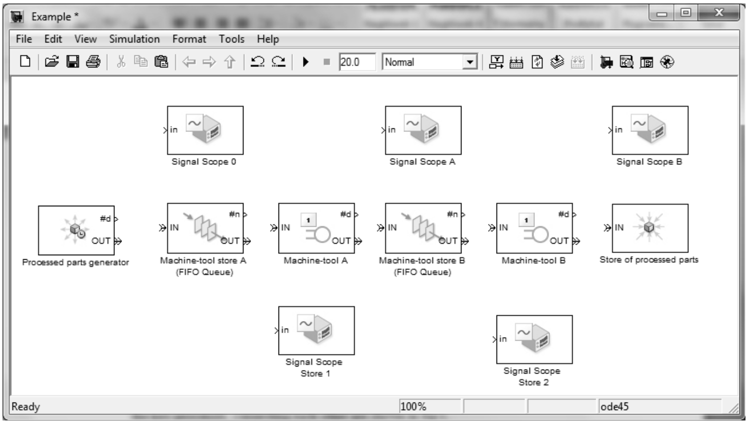

Fig. 5.4. The model of two machine-tools production line

The next step in the process of building model is configuring the blocks. Configuring the blocks means setting their parameters appropriately to represent the system being modeled. Each block has a dialog box that enables to specify parameters for the block. The example of dialog box for *Machine-tool store A* block was shown in fig. 5.5. In presented example of manufacturing lines there are following key parameters of blocks:

- *Processed parts generator* – Period: 1;
- *Machine tool A* – Service time: 2;
- *Machine tool B* – Service time: 1,5;
- *Machine tool store A, Machine tool store B* – Capacity: 25.

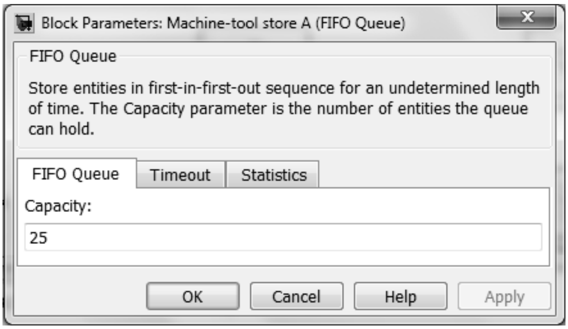

Fig. 5.5. Machine-tool store A – dialog box

The last step in building the simulation model is connecting blocks. Connecting is realized by dragging with the mouse from the output port of the source block to the input port of the destination block or by selecting the source block and making

Ctrl+click the destination block. The example model contains blocks that represent the key processes, connecting each other are shown in fig 5.6.

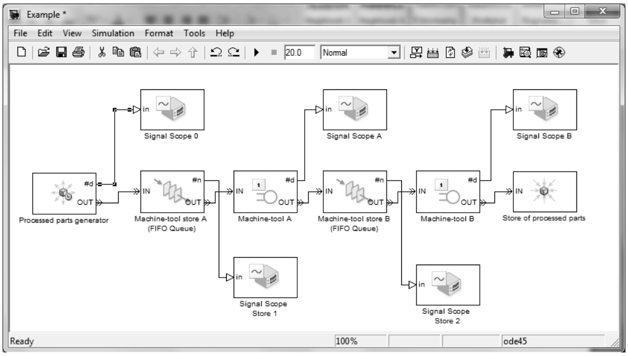

Fig. 5.6. The model of two machine-tools production line with connected blocks

5.4. Analyzing the production flow

Behaving of the model in the Matlab Simevents system can be inspected by:

- Animating – Sim Events support of animation lets to examine the execution behavior of Sim Events model. It can be observed both entity movement and the production and use of events in event-based blocks. For event-based signals, animation illustrates the execution sequence of computation blocks in response to events.
- Using statistics and scopes – most SimEvents blocks can output statistics that let monitor aggregate measures, such as average service times, queue lengths and server utilization. Custom scopes enable to visualize these signals using familiar staircase and stem plots.
- Debugging – the SimEvents debugger lets use MATLAB functions to suspend a simulation at each step or break point to query simulation behavior. The debugger also creates a simulation log for further inspection of detailed information. Debugging can be realized both discrete-event and hybrid simulations by closely inspecting the events and blocks that process them [15].

In this case the plots were used as a tool for analyzing production flow. In particular the following parameters were observed:

- number of entities (parts) have departed from the server (in case of *Processed parts generator, Machine-tool store A, Machine-tool store B*, parts),
- number of stored entities (parts) - (in case of *Machine-tool store A, Machine-tool store B*).

When the simulation of the production process runs, the Signal Scope blocks open windows containing plots. The horizontal axes represents the times at which entites depart from the server or are stored in magazine, while the vertical axes represents the total number of entities that have departed from the server (in case of: *Signal scope 0, Signal scope A, Signal Scope B*) and the total number of stored entities (in case of: *Signal Scope Store 1, Signal Scope* *store 2*). After an entity departs from the *Signal scope 0, Signal scope A* or *Signal Scope B*, the block updates its output signal at the #d port. The updated values are reflected in the plot and highlighted with plotting markers. In case of *Signal Scope Store 1* or *Signal Scope store 2* the block updates its output signal at the #n port. The plots generated during simulation process (the time of simulation was accepted as 20 s.) are shown in fig. 5.7 and fig. 5.8.

From the received plots, it is possible to make following observations:

- starting at T=1, the plot is a stairstep plot;
- each entitle departs from the Processed parts generator every second, as was parameterized in the model,
- until T=2, no entitles depart from the Signal scope A. This is because it takes two seconds for the Machine-tool store A to process the first entity;
- until T=3,5, no entitles depart from the Signal scope B. This is because it takes two seconds for the Machine-tool store A and one and a half for the Machine-tool store A to process the first entity;
- only eight of twenty parts were processed during the time of simulation process (the time of simulation was 20 seconds) – all of 20 parts depart the Processed parts generator, nine parts depart the Machine-tool A while only eight of them depart were transferred to the Store of processed parts;
- the number of entitles was continuously growing in the Machine-tool store A; This is because the each entitle departs from the Processed parts generator every second, while time of processing part on Machine-tool store A takes two seconds. It means that the production flow is not fluent;
- number of entitles stored in Machine-tool store B have not exceed the level of two parts. This is because the time of processing for the Machine-tool B isn’t longer than time of processing for the Machine-tool B and parts are immediately transferred to the Store of processed parts;
- Machine-tool A is the bottle neck of the production process.

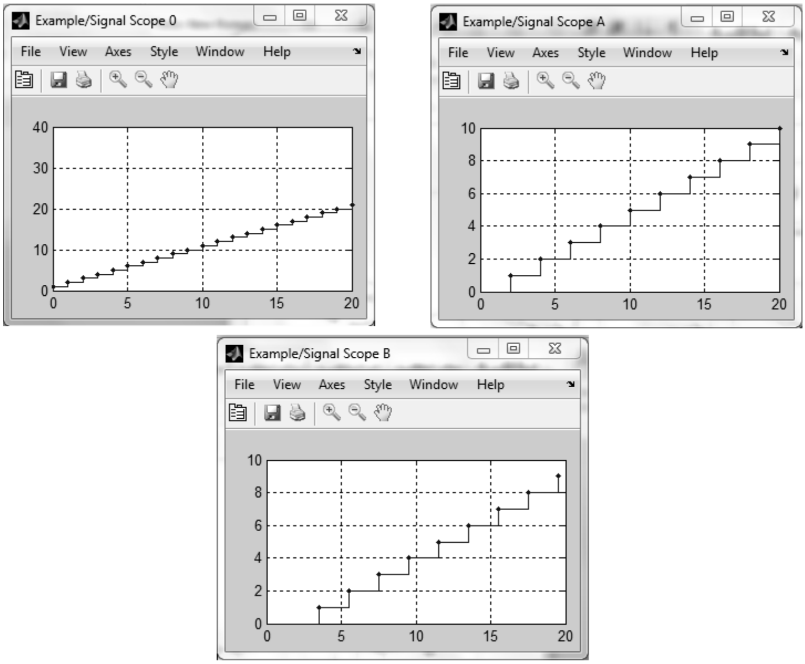

Fig. 5.7. Signal Scope 0, Signal Scope A, Signal Scope B plots

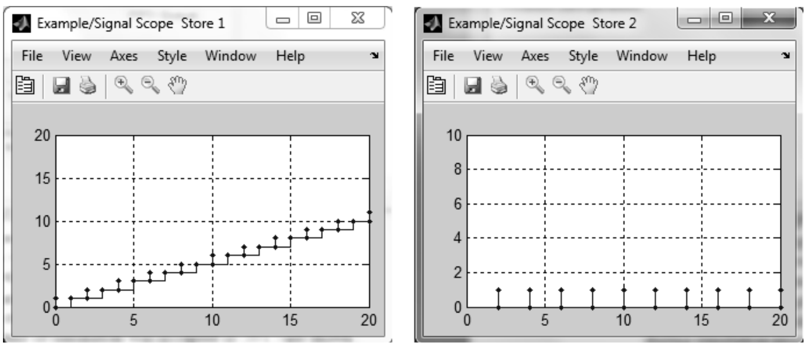

Fig. 5.8. ***Signal Scope Store 1, Signal Scope Store 2*** **plots**

Conclusions

Modelling is commonly used for understanding, engineering and operations of systems. Simevents – simulation engine and component library of Matlab is used to model process flows and logistics in order to understand resource availability, inventory management techniques, and the effects of arbitrary events on a mission critical network design. System capacity planning and production planning can simulated while ascertain its optimal performance [6].

In this paper, we have presented MATLAB Simevent as a tool which can be used for optimization production flow on the simple example of two machine-tools manufacturing system. When modelling the real manufacturing systems or manufacturing processes it is very important to model the system or process in close approximation to the real system and incorporate most of its salient features as well as not being unnecessarily complex such that it is impossible to understand and experiment with it. The major objective of a model is to enable an expert predict the effect of changes to the system. A good model is a meticulous trade off between objectivity and simplicity.

References

[1] Banks J., Carson J.S., Nelson B.L., Nicol D.M : Discrete-Event System Simulation, Prentice Hall, USA, 2010.

[2] Cassandras C.G., Lafortune S.: Introduction to Discrete Event Systems, Springer US, 2008.

[3] Clune M.I., Mosterman P.J., Cassandras C.G.: Discrete Event and Hybrid System Simulation with SimEvents, Proceedings of Eighth International Workshop on Discrete Event Systems, 2006, pp. 386-387.

[4] Gola A., Osak M.: Modelowanie podsystemu obrabiarek w ESP części klasy korpus z wykorzystaniem program Enterprise Dynamics, Postępy Nauki i Techniki, nr 6/2011, s. 66-73.

[5] Gola A., Świć A.: Algorytm generowania ścieżek technologicznych w procesie doboru obrabiarek, Zarządzanie przedsiębiorstwem, nr 1 (2011), s. 8-16.

[6] Inyiama H.C., Udeze C.C., Okezie C.C., Okafor K.C., MATLAB Simevent: A Process Moedl Approach for Event-Based Communication Network Design (A Case for Reengineered DCN), Journal of Basic and Applied Scientific Research, 2012, Vol. 2, No. 5, pp. 5070-5080.

[7] Mrozek B., Mrozek Z.: Matlab i Simulink. Poradnik użytkownika, Wyd. Helion, Gliwice 2010.

[8] Mrozek B., Mrozek Z.: Matlab. Leksykon kieszonkowy, Wyd. Helion, Gliwice 2010.

[9] Ostanin A.: Metody optymalizacji z Matlab. Ćwiczenia laboratoryjne, Wyd. Nakom, Poznań, 2009.

[10] Potter S.: Modeling Control Logic and Event-Driven Systems with Stateflow and SimEvents, Mathworks Webinars, ftp://ftp.mathworks.com/pubs/seminars /SimEventsStateflowWebinar Files/PresentationSlides.pdf

[11] Pratap R.: Matlab 7 dla naukowców i inżynierów, Wyd. PWN, Warszawa 2010.

[12] http://www.incontrolsim.com

[13] http://www.flexsim.com

[14] http://www.arenasimulation.com

[15] http://www.mathworks.com

SIMULATION OF PRODUCTION FLOW USING MATLAB SYSTEM

Abstract: The article presents ability of the Matlab system as a tool which allows to model, simulate and optimize production flow. In particular the process modelling of discrete manufacturing production system, the way of running the simulation and the way of generating scopes on the base of simulation process were shown. The simple model of two machine-tools production line was exploited as subject of the simulation process.

Key words: simulation, MATLAB, production processes SimEvents

SYMULACJA PROCESÓW PRODUKCYJNYCH Z WYKORZYSTANIEM SYSTEMU MATLAB

Streszczenie: W artykule zaprezentowane zostały możliwości zastosowania systemu Matlab jako narzędzia do modelowania, symulacji i optymalizacji przepływu produkcji. W szczególności przedstawiony został proces tworzenia modelu systemu produkcyjnego dla produkcji dyskretnej oraz sposób realizacji procesu symulacji oraz generowania wyników z procesu symulacyjnego. Jako podmiot procesu symulacji wykorzystano dwu-obrabiarkową linię produkcyjną.

Słowa kluczowe: symulacja, MATLAB, procesy produkcyjne, SimEvents

BOGDAN PALCHEVSKYI[*]

6.Information Aspects of Optimization Synthesis of Functional-Modular Structure of Technological Equipment

Introduction

The production cycle in machine building companies, which is the time that parts, components and finished goods spend in the shops, is only 1% of the total time from design to finished goods production. The other 99% fall on the research and development, design and technological preparation of production. Automation and computerization of these phases significantly accelerates the design process.

Fig. 6.1 The scheme of the information technology

The most important trend in the development of methods for designing technological equipment is the creation and development of technology design with use of modern information technologies. The value of information technology in designing great, it creates the information foundation for the development of corresponding sphere of science and its applications.

Information technology in the design, a combination of methods, processes, programming and technical means combined into a chain that provides collection, processing, storage and display of information in order to reduce the complexity of the processes of designing.

6.1. Information-aided design of technological equipment

The peculiarity of using the information technology in the design of technological systems is to use them for modelling of technological equipment and workflow in it. Informational technologies in design are perfectly suited to meet the information needs in creating projects of technological equipment. It is necessary to solve the basic problem of designing - to determine dependences between the structure of the designed object and characteristics of its effectiveness.

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Having some idea of the object of design (conceptual model), a person acquires background information and comparing thereafter the object with its representation forms the design action I_y. It is seen that circuit of information processing stands out, it is separated from the circuit of processing graphical information and becomes independent. The information technologies that convert input information I_{in} the product in the form of background information I_{out} are highlighted in the system. Depending on the human role in the chain I_{ip} - I_{in} - I_{out} - I_y the manual computer-aided, automated and automatic design is distinguished.

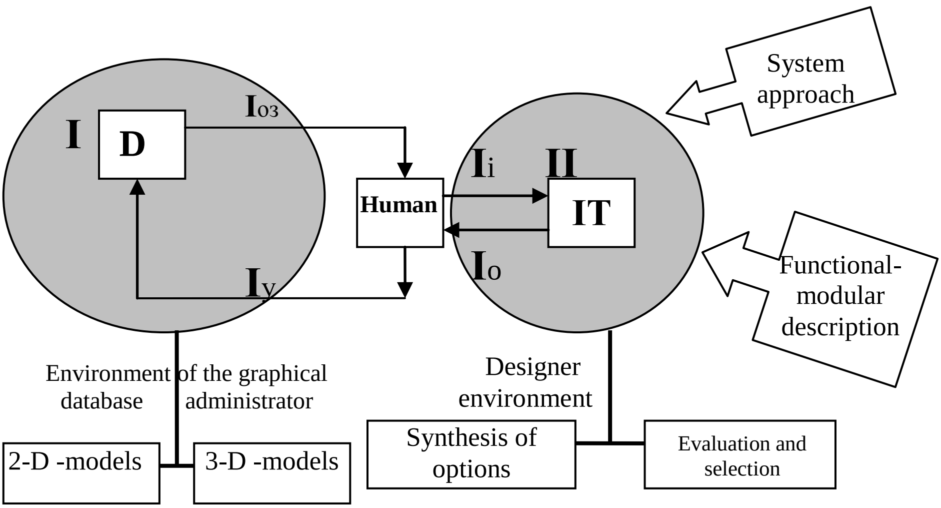

Fig. 6.2 Information system of computer-aided design

The environment of graphical database administrator allows creating and editing drawings and geometric models as well as it is designed to run on hierarchical image databases. Most CAD is reduced to drafting of the already finished technical solution with use of computer programs.

The designer environment provides a solution of all complex tasks of technological equipment designing needed to build the structural, functional and schematic diagram, carry out of necessary calculations, modelling and design. Thus, the design process includes the following stages:

– The components of technological process of packaging are distinguished, technological operations that can be conveniently called functions. These functions arrange the structure of technological process, while several types of functional modules are put in line for each of them.
– The optimal set of functional modules to perform a given task is searched for.
– Next comes the allocation of the functional modules in a certain sequence and establishing connections between them, namely to form spatial layout and functionality for material, information and energy flows in the machine.

The interaction of the defined environments is carried out by using a set of models of object that are divided into two distinctive groups.

1. The first group of models describe the functioning (working) of the future equipment and its component functional modules and processes occurring in it. These models allow us to identify the characteristics of workflows and assess their impact on the technological characteristics of the machine (its performance, reliability and other characteristics).

2. Models of the second group describe the spatial structure of the machine. They allow to determine its size, area, volume, mass and strength under loading.

Models of the first group are usually called functional. The second group of models is based on geometric proportions. They are usually referred as geometric or spatial models.

6.2. Key information technologies of technological equipment design

Arguably, the level of CAD automation is defined by the designer environment. Applying of the information technology in this case should allow obtaining the technical solutions for further comprehensible graphic representation. Therefore, systematic approach that involves presenting of technological equipment as a system that performs a given utility function and functional modules acting as the elements of its structure should be put as the basis for the designer environment. It allows to synthesize the equipment versatile in composition and functions from a limited set of standardized functional modules (FM).

The task of informatization of the part of the technological equipment design process is stated and solved as optimization synthesis of the equipment structure from a unified set of functional modules, i.e. on the basis of functional modularity of design. Functional-modular principle of technological equipment design has the following features:

1. Technological machines of the same purpose perform about the same amount of technological functions.

2. The general utility function of any technological machine is performed by the finite set of functional modules, each executing a complete part of the overall service function of the machine.

3. The structure of technological machine is created by ensuring the functional and spatial connections between the functional elements.

A combination of information technology of synthesis and information technology of optimization (analysis) must be put in the basis of the information process of designing the technological equipment with functional-modular structure.

The design process of manufacturing equipment is customary split into stages (functional and technical, systematic and structural, design). Proceeding from such partition, it is a natural requirement the CAD system to support all phases and levels of the design in full. Unfortunately, in practice this approach is not fully realized.

Information process of design has a set of elementary operations – procedures, which quantity is limited. The main ones are the synthesis procedure and the procedure for selecting options. Of these various combinations of design stages are composed, while the information process of design is composed of the stages combinations.

In developing the methodology of technological systems designing is important to differentiate the process of solutions synthesis (generating options) and the procedure of limiting the diversity of solutions for selecting the best (analysis, evaluation, selection, optimization).

Direct generating of options of the machine structure can lead to their redundancy. Let the facade of 10-storey building have 24 windows on each floor. In the evening, each window can be lit or shaded, that is remain in one of two states. By defining a set of possible states of the building façade, where windows different by their location on the facade whose total number is 10 • 24 = 240 are in one of two states, we obtain:

$$N = 2^{240} \approx 10^{73}$$

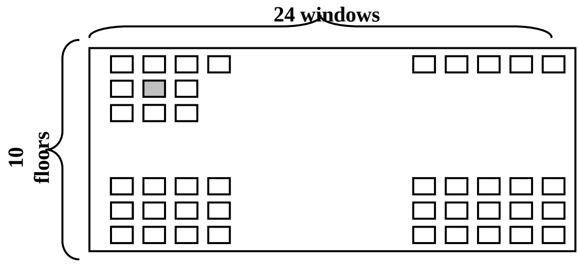

Fig. 6.3 Determining the number of options

The resulting number is extremely large; it corresponds to the number of atoms in the visible universe, which is also equal to approximately 10^{73}.

This example shows that with significant number of structure elements the set of options becomes very large, and the review and evaluation of all possible structures is impossible. For this purpose the special methods of synthesis, a feature of which is to impose additional conditions on the obtained structure, are used.

In practice, during the design process the space of solutions is restricted by studying only certain combinations of elements. As a result of selection only those options remain that have "better" value of the optimization function compared to the previous iteration. In order not to miss the best solution in the design process one need to include the information synthesis procedure reducing capacities of sets obtained at different stages, namely:

1. Technology of the directed synthesis. The design process is an analysis of the product and determining the sequence of the formation of components. The result is a sequence of technological operations, which specifies the sequence of functional modules during the synthesis of structure.

2. Synthesis technology with limited set of options based on typical mathematical models which allows to consider a number of restrictions for the options of structure.

3. Synthesis technology with limited set of structure options by using the "and-or" tree. This tree contains technical solutions in a compact form of information about a specific, pre-formed set of options for the structure of a technical system.

4. Technology of stepwise synthesis and optimization. The design process is an alternation of procedures for forming subsets on different hierarchical levels and their evaluation to select the best one.

5. Technology of hierarchical synthesis. The design process is an aggregated representation of the workflow so that every bigger technological operation can be qualitatively assessed using quality measures for its implementation. Each larger function is associated with a block of functional modules that implements the function. Then when combining options modular structure the set of options considered is much smaller.

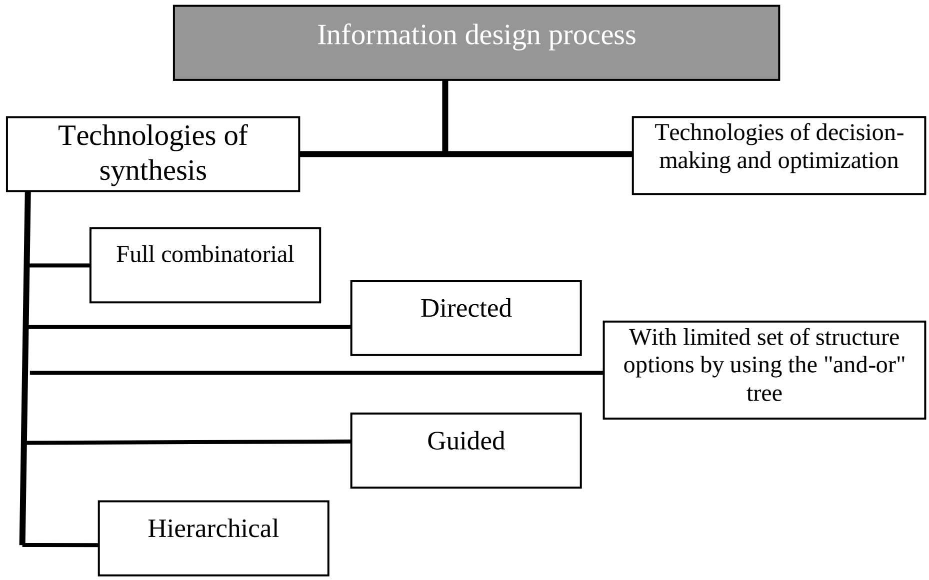

Fig. 6.4 Specialized methods of the synthesis procedure

6.3. Technology of the directed synthesis

It is advisable to improve design technology in a direction that every step taken from concept to finished project was an information procedure on multiple models of the object design. It creates conditions that, starting with the first and ending with the last stage of the project, all information on the results of one phase is used in the following stages during the design. Every previous model actually specifies the additional restrictions that reduce the number of options obtained with combinatorial synthesis on the next step (Figure 6.5). In this case, the process of structural synthesis enables the "top-down" design and gets the optimal structure that fits in the above specification and boundary conditions.

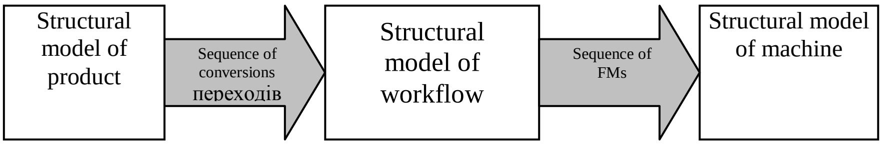

Fig. 6.5 Sequence of the system models use in the directed synthesis

The sequence of steps of the workflow defines the product design, analysis of which allows to set the sequence of the forming its components. As a result, a sequence of technological conversions that form a workflow is determined. The structure of a workflow defines a sequence of functional modules in the structure of the machine.

The design begins with the analysis of the product. Analysis of the structure of traditional machining processes, for example, shows that the sequence of creating surfaces of a detail is chosen in most cases purely arbitrary. This sequence is set by a designer’s intuition and is far from optimal. If an elementary technological conversion is put in line with the creation of each elementary surface, then it can be assumed for any a single conversion that the conditions for its realization will depend on some previous conversions. On the other hand, this technological conversion, in turn, can affect the implementation of the following ones. That is the surface created on the step is necessary to implement some of the next conversions. Thus, each conversion is characterized by technological input and output cause-ties of in the scheme of machining and therefore should occupy an appropriate place in the structure of processing. In the most general case, the functional, design and technological limitations affect the sequence of surface processing, that can distinguish three groups of contradictions namely:

– functional connection of precedence imposed by the conditions of functioning parts (auxiliary surfaces at first, next the functional surfaces);
– design connection of precedence imposed by the terms of spatial arrangement of surfaces in parts (datum references are processed initially);
– technological connection of precedence imposed by the conditions of part machining.

To determine the logical sequence of processing the functional, geometric and technological precedence ratio that are imposed on the surface details can be written in the form of a precedence matrix.

The surface to be processed previously						
П –the processed surface	П1	П2	П3	П4	П5	**Bo** Level of dependence of the surface
П1						0
П2	1					1
П3	1					1
П4		1	1			2
П5				1		1
Level of following of the surface	2	1	1	1	0	

In this matrix, each connection of precedence between two surfaces is marked as 1. Through formalized procedures developed by A. Kaufmann, a sequence of technological conversions of processing the surfaces of a part is derived divided into 4 stages of processing (Fig. 6.6).

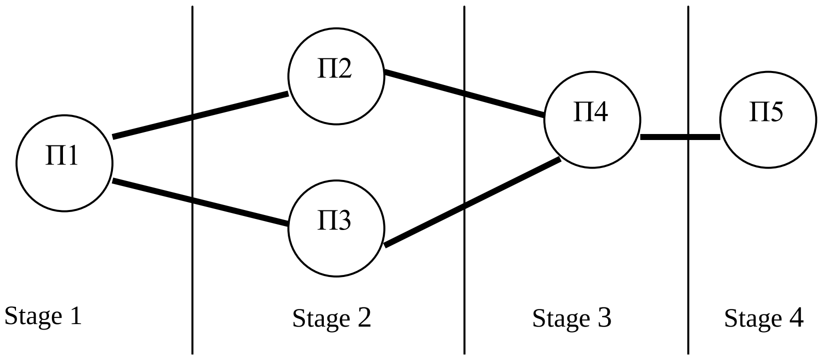

Fig. 6.6 Graph of precedence connections for processing the П1-П5 surfaces

The function of the equipment that performs technological operation implements complex technological transformation that includes a number of simple conversions performed by individual functions and subfunctions φi, i.e.:

$$F \to \{\varphi_1 \cdot \varphi_2 \cdot \varphi_3 \cdot ......\}$$

A subfunction generally consists of two or more elementary functions. The advantage of this method is that for the required performance function several alternative models of workflow can be developed and selected for their optimal suitability at a relatively small cost of time. The structure of the workflow, shown in Figure 6, defines partially ordered sequence of formation of the product, for example, by processing blanks with the state S (0) to the final state S (P5):

$$F = C_0(0)\varphi_1 C_1(\Pi 1) \begin{matrix} \diagup \; \varphi_2 C_2(\Pi 2) \\ \diagdown \; \varphi_3 C_3(\Pi 3) \end{matrix} \Bigg\} \varphi_4 C_4\ (\Pi 4)\varphi_5 C_5(\Pi 5)$$

This record of a workflow structure means the following. Originally the workpiece transferred by means of transition φ1 from the state C0 to state C1 (P1) by processing the surface P1. Next a conversion φ2 or φ3 is possible. A part is shifted into a state C4 (A4) with the φ4 conversion and so on down to a final state C5 (P5). One can see that the order of conversions φ2, φ3 is not regulated. Because even this simplified scheme can build several options of processing that differ by type of machining equipment, degrees of processing concentration, parallel or serial execution of certain operations, the next step is to search for the optimal structure of the part machining process, but the estimated number of options will be significantly reduced.

Under the procedure of constructing the system model of the process is to be understood such activities that are necessary to ensure that workflow in equipment is provided by a structure derived from subfunctions or elementary functions that meet the technological conversions at various levels of complexity.

Functional modeling is a key moment of forming the structure of technological machine because the function model serves like a roadmap that helps designers to reach the desired layout of the machine.

The design process is based on the presence of a design scheme, with alternating design procedures of two types - synthesis and optimization of technical solutions (Fig. 6.7). Structural design is a combination of possible combinations of technology machine's FMs, getting set of layouts and their evaluation for choosing the best. The applied here method of directed search (as the machine workflow defines the sequence of FMs) provides consistent consideration of each of the options structure during sorting.

Consider, as an example, the structural design of the technological machines for the packaging of loose substances.

Technological packaging operation includes technological transitions (x1 – x5) sequence of which can be considered as given:

- forming a tube blank of the package from the polymer film (x1);
- dosing the mass of substance (x2);
- longitudinal welding of package (x3);
- transverse welding of package with a dose of substance in it (x4);
- pulling a tube blank of the package (x5).

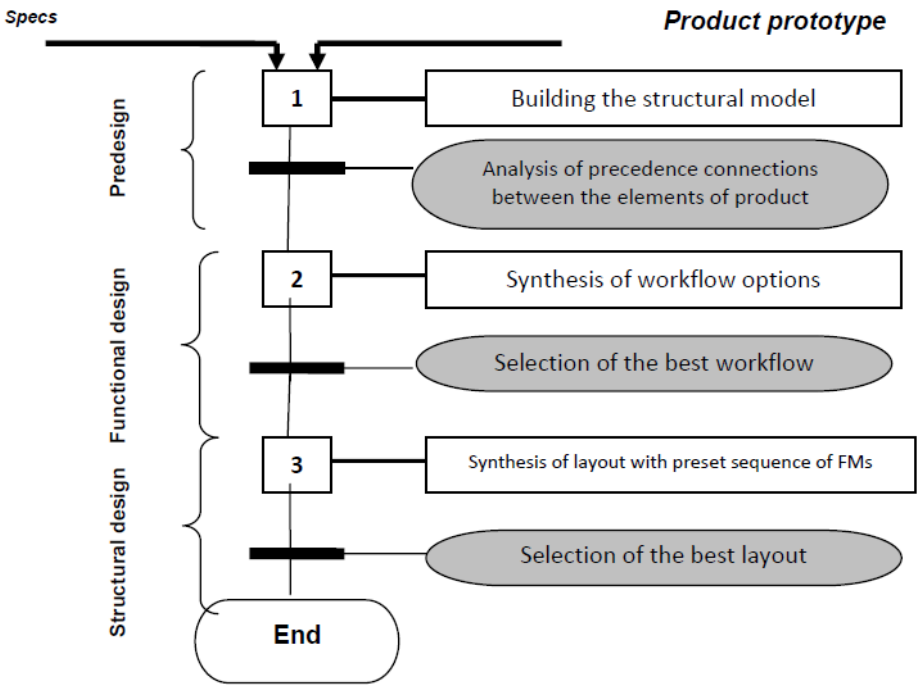

Fig. 6.7 Algorithm for the directed synthesis of technological equipment

Since the implementation of each conversion makes possible the use of FM differing by design and characteristics (reliability, speed, energy consumption, cost, etc.), the problem of packing machine structure synthesis becomes multivariate. Methods of directed search are based on the possibility of gradual rejection of unpromising directions finding the optimal solution (Fig. 6.8). The process of designing is reduced to finding a way (1 - n) on the model that provides the best value of the machine quality. Problems that hidden behind such a simple algorithm become evident while increasing the number of FM in the structure of the machine.

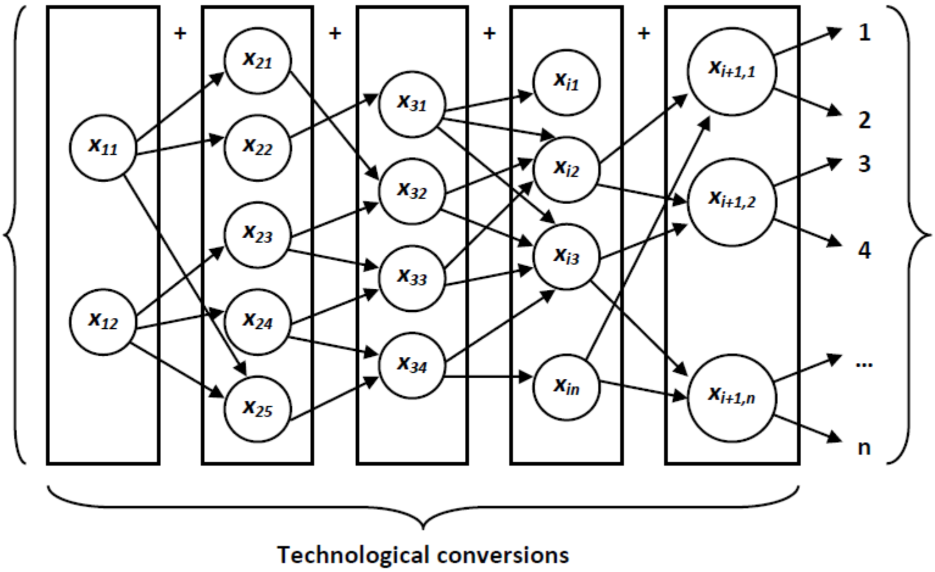

Fig. 6.8. Model of optimization synthesis of a packaging machine of functional-modular structure with preset sequence of FMs

6.4. Synthesis technology with limited set of options based on typical mathematical models

It allows to take into account a number of constraints on the existence of options structure.

The following characteristics of differences between versions of the structure are taken into account:

1. qualitative composition of elements, ie, possible variations of elements that create the object. This feature of the mathematical model is denoted as FE;

2. number of elements that create the object of synthesis. This attribute of the model is denoted as FN;

3. the order of elements in the structure of the object of synthesis. This attribute model is denoted as Fp.

If the content of elements of all the options while generating the structure is the same, then FE = 1 else - that FE = 0. If all the options of structure have the same number of elements, then FN = 1 else FN = 0. If a sequence of combining elements in the structure of all the options is the same, then fp = 1 else - Fp = 0.

Depending on the generated object with certain features of differences between the structure options, the following classes and subclasses of standard mathematical models (Table 6.1) are used.

Tab. 6.1. Classification of mathematical models used for generating the options of structure

Model			Characteristic of generating the option of structure		
Class	Subclass	Name	F_E	F_N	F_Π
Conjunctive	0	MS01 MS02 MS03	1 0 0	1 1 0	- - -
Organizing	Table - 1	MS11	1	1	1
	Network - 2	MS21 MS22	0 0	1 0	1 1
	Permutation 3	MS31 MS32 MS33	1 0 0	1 1 0	0 0 0

Let us consider example of a typical model MS31 to generate variants of the technological process of assembling the product. Technological operation of assembly is associated with installation of one of the components (Figure 6.9).

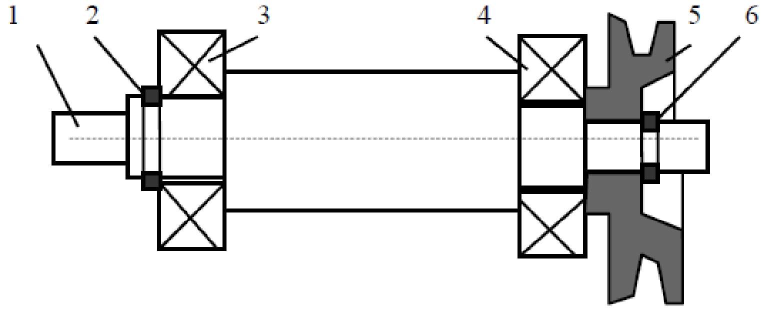

Fig. 6.9. Drive mechanism. 1 – shaft, 2,6 – retaining rings, 3,4 – bearings, 5 - pulley

All possible sequences of combinations of parts are described completely by graph on six vertices. Each of the options of assembly process is set by a covering tree of this graph. Total number of covering trees and thus options of assembly sequence is determined by Cayley's theorem and is

$$n_{T\Pi} = p^{p-2} = 6^4 = 1296,$$

where p – is a number of vertices

Obviously, the set of assembly processes obtained by formal enumeration of graphs include many unrealistic and absurd choices, the analysis of which is unnecessary. Therefore, the use permutation model which significantly limits the number of options eligible for consideration, greatly simplifies the process of optimization synthesis. First of all, only the variations of the process, starting from the operation of setting the part 1 (basic part of the mechanism) are taken into account. When considering the possibilities to access other parts the number of options process will be reduced to ten (Table 6.2). In Table 6.2 the following notation is used: 1 – install the shaft 1 in the assembly device; 2 – install retaining ring 2; 3 – install the bearing 3; 4 – install the bearings 4; 5 – press the pulley 5; 6 – install retaining ring 6.

Tab. 6.2. Options of the drive mechanism assembly process

№	Assembly sequence	№	Assembly sequence
1	1-3-2-4-5-6	6	1-4-3-5-6-2
2	1-3-4-5-6-2	7	1-4-3-5-2-6
3	1-3-4-2-5-6	8	1-4-5-3-6-2
4	1-3-4-5-2-6	9	1-4-5-3-2-6
5	1-4-3-2-5-6	10	1-4-5-6-3-2

6.5. Technology of the stepwise optimization synthesis

The methods controlled search are based on the possibility of gradual rejection of unpromising directions while finding the optimal solution. The design process is the successive addition of the specific functional elements to the machine at each stage and the evaluation of the result. The assessment procedure is shown as a logical transition to the next stage of design (Fig. 5.10).

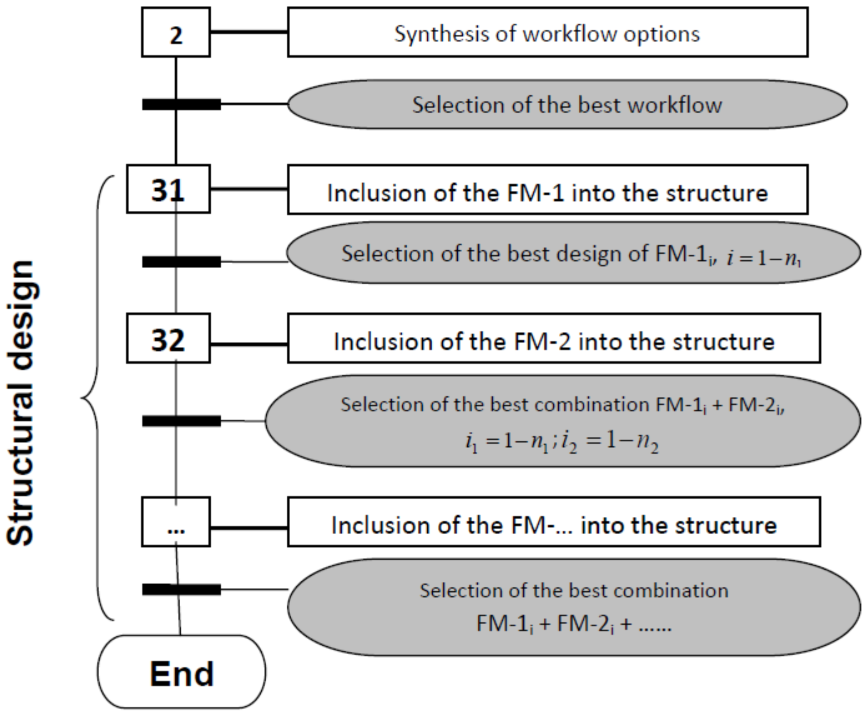

Fig. 6.10 Algorithm for the stepwise directed synthesis of technological equipment

The peculiarity of this synthesis is additivity of the criterion for evaluation and selection of layout design at each step. These criteria include the cost of FM, its weight, energy consumption, etc. It should also be noted that the sequence of joining FMs to a machine can be both direct, i.e. starting from first technological conversion FM and reverse when step by step synthesis starts from the last (terminal) FM.

6.6. Technology of hierarchical synthesis

To facilitate the search for proper layout and accelerate virtual search extensive libraries on the principle of building blocks performing the most complicated part of the machine workflow, are currently being formed.

The design process is an aggregated representation of the workflow of equipment so that every bigger technological operation or conversion can be assessed using quality measures for its implementation. Each enlarged function is associated with a correspondent block of functional modules. Thus, when combining the modular structure the set of options considered becomes significantly smaller.

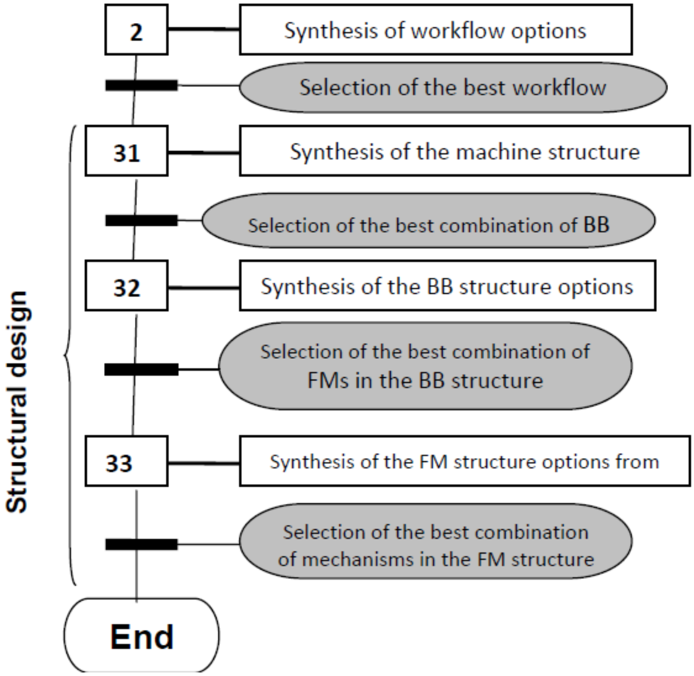

Fig. 6.11. Algorithm of hierarchical synthesis

Applying the hierarchical synthesis of functional-modular structure allows presenting a packing machine as a combination of three units: BB-1 – a dosing unit, BB-2 – package forming unit and BB-3 - auxiliary functions unit (Fig. 6.12).

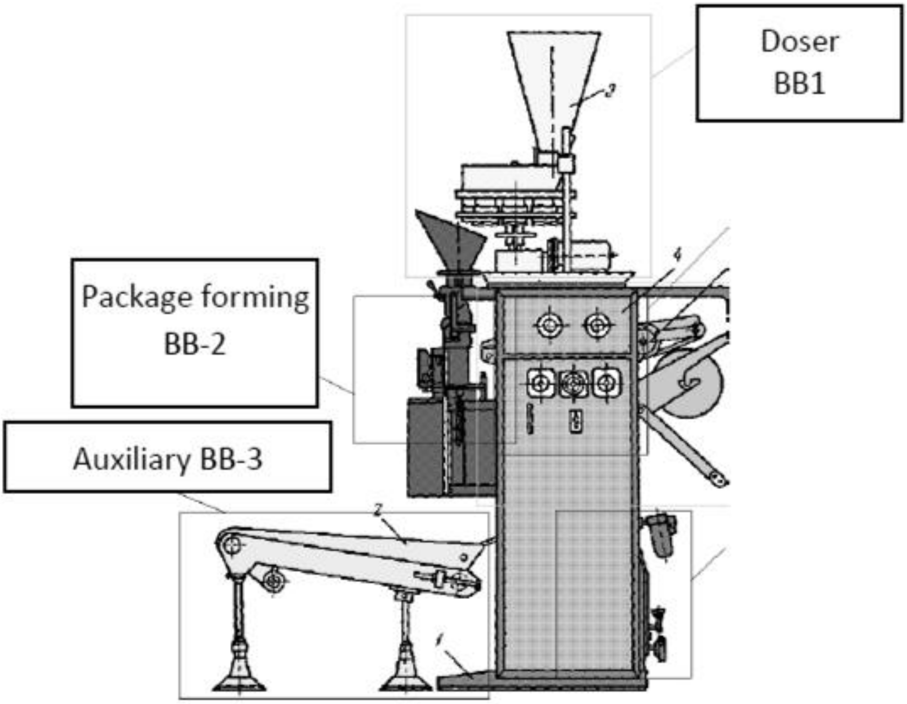

Fig. 6.12 Packaging machine design of three BBs

A distinctive feature of the use BB is as follows:

1. Few parts in BB can be developed more thoroughly using the methods of analysis and modeling that are inaccessible to a large array of connections. This allows to obtain more reliable results.
2. Second, a smaller number of structural units facilitates combinatorial processes.

References

[1] Пальчевський Б.О. Інформаційні технології проектування техно-логічного устаткування. Монографія.-Луцьк: Луцький НТУ, pp. 2012.-572.

[2] Palczewski B., Zasady modularyzacji w projektowaniu technologicznych systemow pakowania // Zeszyty naukowe Politechniki Rzeszowskiej, 2006, № 230, MECHANIKA, z.67.- s. 51-60.

[3] Пальчевський Б.О. Оптимізаційний синтез модульної технологічної системи // Машинознавство, 2001, № 6.- pp. 26-30.

INFORMATION ASPECTS OF OPTIMIZATION SYNTHESIS OF FUNCTIONAL-MODULAR STRUCTURE OF TECHNOLOGICAL EQUIPMENT

Abstract: The paper presents the information approach to the design of equipment with functional-modular structure. The advantages and drawbacks of various technologies of synthesis are shown.

Key words: information technology, technological equipment, design, synthesis, structure

INFORMACYJNE ASPEKTY SYNTEZY I OPTYMALIZACJI FUNKCJONALNO-MODUŁOWEJ STRUKTURY URZĄDZEŃ TECHNOLOGICZNYCH

Streszczenie: Przedstawiono podejście informacyjne do projektowania urządzeń z funkcjonalno-modułową strukturą. Podano wady i zalety różnych technologii syntezy.

Słowa kluczowe: technologie informacyjne, urządzenia technologiczne, synteza, struktura

*PIOTR PENKAŁA**

7. Flexible manufacturing system for machining parts of a body

Introduction

Parts of the body class are widely distributed in each machine, and can be present on each device. The variety of them is large, which results in the problem of their distribution. The bodies act as a skeleton to provide adequate strength and contain some pick-up points and support components. Body structures and their dimensions are characterized by a great diversity. The bodies belong to the most difficult part of the each machines. With their design should pay particular attention to the design manufacturability. It has a decisive impact on the treatment and the effort and quality. Do not keep manufacturability may require that the treatment of bodies could be difficult or even impossible. The condition for the development of the structure meets the main criteria for manufacturability, having the required properties of utility, is working closely with manufacturing engineers.

Machining requirements set by the class constructors body parts relate primarily to the accuracy of the implementation of the major surfaces and holes. The surface roughness of Ra = 1.25 ÷ 0.32μm, flatness, accuracy of position (paralleland perpendicular), and their position relative to the hole [1].

7.1. Setting up a flexible manufacturing system for the type of body

Machining module concept is known in the field of organization of production using conventional machines and technological equipment. Flexible manufacturing modules (FMM) refer to flexibly automated production, in which almost all levels of the production is used for microprocessors and computer control.

As a result, changes are not only the organization of the production unit, but most of all technical means used in the production, control and transport. Flexible manufacturing modules are defined as a set of automated flexible machine tools with NC or CNC controlled, selected and arranged according to the tasks assigned to them, each with integrated transport, storage and common computer control. The structures may also be other positions as control, washing and drying. Obligatory equipment is computer controlled and integrated local area network LAN connection to a central computer unit production [2].

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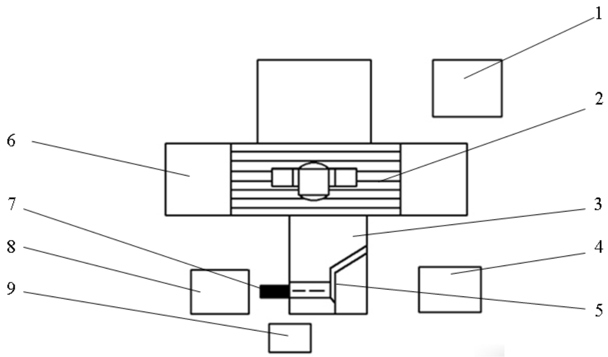

Fig. 7.1. Linear setting FMM for machining the body of the class [2]

1- numerical control system
2 - part of the clamping device
3 - stand
4 - unloaders
5 - robot
6 – machine
7 - universal grippers
8 - the loading
9 - FMM control

Figure 7.1 shows the linear arrangement of FMM for machining parts of a body with a mass of 5 kg and overall dimensions of 200 mm. The module is built on a machine (6) and 103M LF26OMF3.21 model LP-200 numerical control (1), robot (5) models TUR-lO, PREM-5, "Cyclone-5". Construction of universal grippers (7) are set on the base (3). In addition, the clamping device consists of FMM course (2), the loading device (8) and unloading (4), and block binding FMM control device (9). FMM covers an area of 20 m^2 [2].

World leader in the construction of flexible machining modules seems to be Fastems Finnish company that built and installed since 1982 in Europe, more than 800, and in the U.S. about 100 systems with machine tools derived from over 40 manufacturers. Fastems company acting as a systems integrator offering complete systems including FMS [3]:

- different sized systems with different dimensions of pallets and machine tools according to customer needs,
- flexible production from single parts to serial production,
- control based on its own software modules known as Windows 2000/XP platforms, from single machines to large production systems,
- customer support strategies in the planning and scheduling of production,
- guarantee of 96% availability,
- opportunity to include fitting functions.

Fastems's systems are configured and built with modules. One example is shown on Figure 7.2 [3].

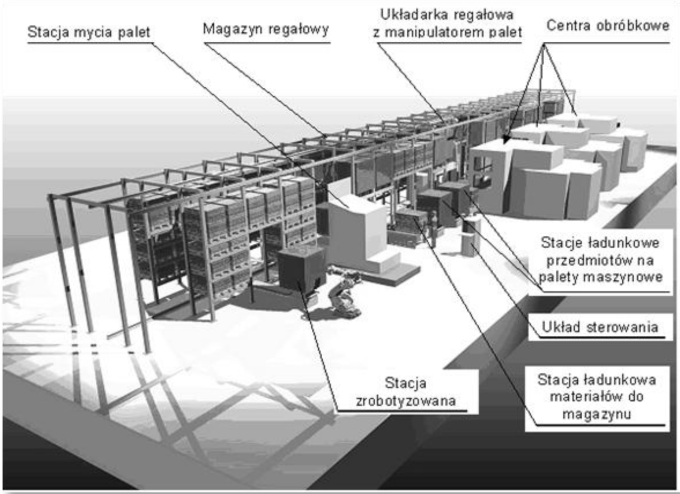

Fig. 7.2 Flexible modulus of Fastems [3]

7.2. Determination of the manufacturing process of the body

For the analysis the body shown in Figure 7.4.

7.2.1 Selection of blank

The most important factors that will influence the selection of the blank are:
- production,
- shape of the object,
- object or material specific guidance on technical conditions.

The blank for the body will become a cube with dimensions of 106x100x126 mm - Figure 9.3, obtained by cutting the strip.

7.2.2. Design manufacturability analysis

An important issue for economical reasons is to analyze the manufacturability of the structure. The considerations as to which of the many possible constructions is the best in terms of technology should be taken into account in particular:
- production,
- owned the means of production,
- the so-called opportunities – cooperation, namely to obtain some of the bands, or even a single specialized parts of other plants [4].

Work piece machining method will be used for machining of the body. Despite the relatively small size is part of a complex construction. The body is made of aluminum alloy PA6 (AW-2017A).

It is characterized by low resistance to corrosion, good machinability and susceptibility to stamping or bending. His choice was determined by the strength and good machinability, better than, say, PA11 aluminum alloy, which makes chips sticking to the cutter [5]. They have to take this into account, as the treatment will require high-speed rotary cutters.

Analysed the body has a high degree of complexity. It results that a large variety of shapes. Will be made of a single material. For its implementation will be used only treatment method machining. This section, a small tolerances imposed on the shape and position, in particular of parallelism and perpendicularity of the basic surface. This body will require a minimum number of attachments to the above conditions have been met, thus ensuring only the five-axis milling center.

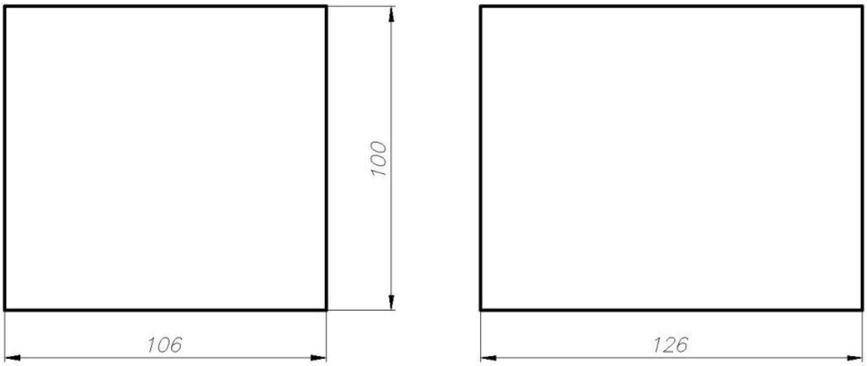

Fig. 7.3. Drawing a blank body

7.2.3. Run of manufacturing process

Based on the criteria adopted for machining, manufacturing process the body will be conducted as follows:

- operation 10 (cutting material) - 106x100 cut the length of the material 126,
- operation 20 (milled dovetail) - milled dovetail respecting the dimension sketch,
- operation 30 (mill body by the PR1001),
- operation 40 (remove the dovetail) - milled dovetail with– overmeasure maintaining dimension 84,
- operation 50 (quality control body) - check the correctness of the implementation of the data in Figure executive.

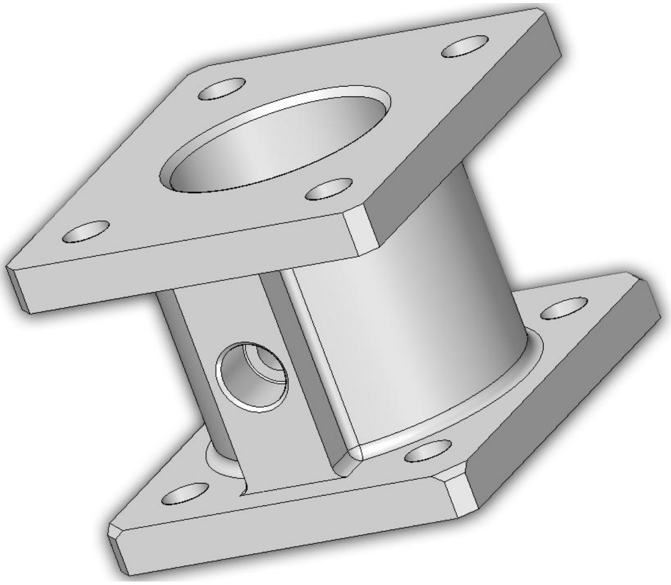

Fig. 7.4. Solid model body

7.3. Selection of the main elements of flexible machining system

Flexible machining module is composed of three machines and a range of technological equipment and assistive devices.

7.3.1. Hermle Milling Center UP C30

Machine tool used to carry out this operation 30 process (Fig. 7.5). Milling center HERMLE UP C30 is very efficient machine tool the construction of the portal. The body is cast mineral base with three-point mountings, solid monoblock. The movement in the Y-axis spindle is supported by three guides and has a range of 450 mm. In the case of the X-axis range is 600 mm, and 450 mm in the Z-axis. The center has digital drives A and C, ball screws, and direct measuring system in all axes. The machine is equipped with a spindle speed of 18,000 rev / min and 15 kW with controlled deformation zone. The standard version of the machine has a rapid traverse and work up to 45 m/min and has a magazine for 29 tools [6].

Fig. 7.5. Five-axis milling center Hermle C30 UP [6]

7.3.2. Two numerical milling machine VMC 1000

Machines were used for the operation of 20 and 40 process (Fig. 7.6). The main advantages of the machine are [7]:

- extremely rigid construction through the use of first-class mechanical components from known and reliable suppliers,
- large working space and the largest on the market the performance data tables,
- wide range of the most popular CNC controls to choose from: Heidenhain, Siemens, Fanuc,
- extremely rich standard design and many options of accessories– high accuracy and high dynamics,
- wide range of applications, meeting the requirements of modern factories and workshops.

Fig. 7.6. Numerical Milling VMC 1000 [7]

7.3.3. Industrial articulated robot Kuka KR 210 R2700 PRIME

It’s primary purpose is to transfer the system to the position of the reinforcement pallet machine. KUKA Robotics as a pioneer in conducting bidder is in industrial robots (Fig. 7.7). KUKA today offers a complete range of industrial robots and robot systems, covering all the necessary class capacity. The robot runs on the proven PC-based control platform. This control allows the robot to use all the technological advantages such as remote diagnosis, Microsoft Windows interface, fieldbus, Soft PLC, OPC Server and much more. Slimmer, lighter, and extremely rigid and precise yet. Short cycle times, superior accuracy of track work and high energy efficiency. The robot KUKA KR 210 is a new class of power for many applications [8].

Fig. 7.7. Articulated robot KUKA KR 210 R2700 PRIME [8]

7.3.4. PW 160 pallet changer

Hermle Machine UP C30 shown in Figure 5 has a pallet changer PW 160 shown in Figure 7.8. Depending on the pallet changer, the machine may have from three to seven.

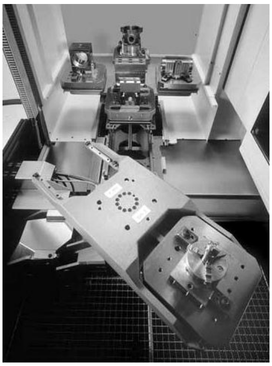

Fig. 7.8. Mode of transport pallets machine Hermle C30 UP (in stock pallets) [6]

PW 160 pallet changer Hermle company can work with different models of C series changer machine is 2.5 m^2 and an additional 1 m^2 needed for storage.

The main advantage of the system is the ability to manipulate three pallets at the same time, or even seven, if you install additional storage. Pallet management software with integrated machine control. Double gripper can transport pallet weighing up to 160 kg (with mounting deviceand subject to earlier) from the position of the reinforcement to the working area. Changer is a separate component of the machine and can be set up without foundation.

7.3.5. Store additional tools ZM

With many standard treatments capacity storage for tools is not enough. For this reason, additional storage was developed. The magazine also makes available to the existing storage space in the machine, one or more storage rings.

Machine Hermle C30 UP may have additional storage for tools that can accommodate the number of tools from 47 units to 162 (Fig. 8.9). This warehouse is controlled by a control system SOFLEX company called SOFLEX - TCS.

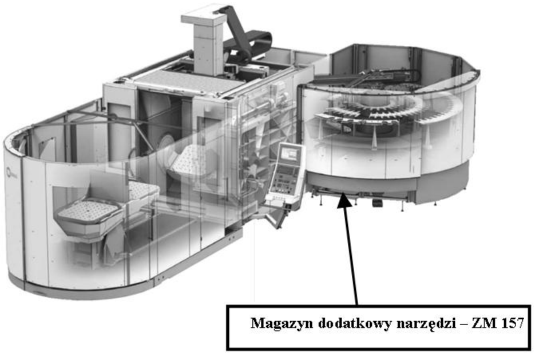

Fig. 7.9. Example machine Hermle C30 magazine holding UP at 157 additional tools [6]

Summary

Manufacturers of machinery for the manufacturing industry seeking to increase the efficiency of its equipment, and maintenance of facilities on globalized markets without modern automated systems impossible. With flexible production and high precision products must shorten the processing time while still must be ensured high reliability.

The increase in the cost of human labor makes obsolete devices are increasingly being transferred to countries where direct human labor is cheaper. If production is expected to remain in the home country, the solution is to implement automated, including robotic means of production. These devices will ensure the operation of expensive machine tools in their free time for service - at night, on Saturdays, Sundays, holidays, and this will provide a significant reduction in production costs. Manufacturers of machine tools and automation components seek to ensure the highest productivity, while adapting its products to be installed and operation in saving funds. One of the main ways to increase the productivity of production is endeavoring to increase the working time of machines by automating the flow subsystem objects and provide maintenance-free operation in your spare time. Developed and implemented a system is an example of the philosophy presented in the main part of the production machines.

References

[1] Feld M.: Podstawy projektowania procesów technologicznych typowych części maszyn. WNT, Warszawa 2000.

[2] Kosmol J.: Automatyzacja obrabiarek i obróbki skrawaniem. WNT, Warszawa 2001.

[3] http://www.energoelektronika.pl/do/ShowNews?id=1450&spis_artykulow,

[4] Choroszy B.: Technologia maszyn. Oficyna wydawnicza Politechniki Wrocławskiej, Wrocław 2000.

[5] Dobrzański L.: Podstawy nauki o materiałach i metaloznawstwo, WNT, Warszawa 2002.

[6] http://www.hermle.de

[7] http://www.akrostal.pl/pl/strony_p_75,47,2,18HGT.html

[8] http://www.kuka-robotics.com/poland/pl/

FLEXIBLE MANUFACTURING SYSTEM FOR MACHINING PARTS OF A BODY

Abstract
The paper analyzes the flexible manufacturing systems for the body type. Digital is made of a solid model. After analysing the manufacturability of the selected body developed an operational plan. On the basis of the basic information technology machines chosen for achieving the planned machining process. Selects the assist devices: robot, pallet changer and an additional tool magazine. Developed a flexible manufacturing system has been tested in an industrial environment.

Keywords: body, manufacturing process, flexible manufacturing system

ELASTYCZNY SYSTEM OBRÓBKOWY DO OBRÓBKI CZĘŚCI TYPU KORPUS

Streszczenie
W opracowaniu dokonano analizy elastycznych systemów obróbkowych dla części typu korpus. Wykonano cyfrowy model bryłowy części. Po dokonaniu analizy technologiczności wybranego korpusu opracowano plan operacyjny. Na bazie podstawowych informacji technologicznych wybrano obrabiarki do realizacji założonego procesu obróbkowego. Dobrano także urządzenia wspomagające: robot, zmieniacz palet oraz dodatkowy magazyn narzędzi. Opracowany elastyczny system obróbkowy został sprawdzony w warunkach przemysłowych.

Słowa kluczowe: korpus, proces technologiczny, elastyczny system obróbkowy

*PIOTR JAREMEK**

8. Comparative analysis of methods for assessing the durability of roller cones bits

How to provide drilling operational the roller cones lifetime in the first place depends on the durability of their bits especially at the number of revolutions up to 300 rev/min. At the moment it was not developed an effective method of calculation which allows to predict durability of roller cone bits at their given wear. The articles [1, 2] presents a method based on the well-known jointed – tribological sliding friction interaction. The base model and modified models of wear kinetics of roller cones bits was built, on the basis of this model. Based on this prediction of durability, wear and mechanical drilling speed was conducted for the selected type of roller cones and some specific drilling parameters.

Results of tooth wear changes h_i, during the drilling process, in extreme rims as a function of axial thrust N and rotation speed n_1, shown in [5,6]. Calculations carried out by both methods show that wear of bits is more intensive within the first hour of drilling than after six hours. In [3,4] presents a method for evaluation of bits durability on the basis of the results obtained earlier wear, while in [7] was carried out analysis of the influence of drilling parameters to said durability. The following equations were used for the presented calculation methods.

The method I

- model of a first degree (I.1)

$$T_i = \frac{AR_{oi}\tau_t^m h_{**}\left(e^{cm\frac{h_*}{h_{**}}} - 1\right)}{60u^2 n_1 R_i s_i \tau_o^m cm} \tag{8.1}$$

- model of the second degree (I.2)

$$T_i = \frac{AR_{oi}\tau_t^m h_{**}\left(e^{cm\frac{h_*}{h_{**}}} - 1\right)}{60u^2 n_1 \left(R_i - h_* \cos\delta\right) s_i \tau_o^m cm} \tag{8.2}$$

- model of the third degree (I.3)

$$T_i = \frac{AR_{oi}\tau_t^m}{60u^2 n_1 s_i \tau_o^m} \cdot \int_0^{h_*} \frac{e^{cm\frac{h}{h_{**}}}}{R_i - h\cos\delta} dh \tag{8.3}$$

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where:

$$\tau_o = f \cdot \sqrt{\frac{E \cdot N \cdot [1-\sin(0.5\gamma)]}{\pi(1-\nu^2)\cdot l_\Sigma \cdot [0.5l\cos(0.5\gamma)]}} \tag{8.4}$$

The method II

- model of a first degree (II.1)

$$T_i = \frac{A\tau_t^m R_{oi}}{60R_i s_i f^m u^2 n_1}\left(\frac{\pi(1-\nu^2)l_\Sigma}{EN\left(1-\sin\frac{\gamma_i}{2}\right)}\right)^{\frac{m}{2}} \frac{\left[\left(h_*\sin\frac{\gamma_i}{2}+\frac{l}{2}\cos\frac{\gamma_i}{2}\right)^{\frac{m}{2}+1}-\left(\frac{l}{2}\cos\frac{\gamma_i}{2}\right)^{\frac{m}{2}+1}\right]}{\left(\frac{m}{2}+1\right)\sin\frac{\gamma_i}{2}} \tag{8.5}$$

where:

$$M_i = \frac{R_{oi}A\tau_t^m}{60u^2 f^m R_i n_1 s_i}\left[\frac{\pi(1-\nu^2)l_\Sigma}{NE\left(1-\sin\frac{\gamma_i}{2}\right)}\right]^{\frac{m}{2}}\left[\left(\frac{m}{2}+1\right)\sin\frac{\gamma_i}{2}\right]^{-1},$$

$$D_i = \left(\frac{l}{2}\cos\frac{\gamma_i}{2}\right)^{\frac{m}{2}+1}.$$

- model of the second degree (II.2)

$$T_i = \frac{A\tau_t^m R_{oi}}{60(R_i - h_*\cos\delta)s_i f^m u^2 n_1}\left(\frac{\pi(1-\nu^2)l_\Sigma}{EN\left(1-\sin\frac{\gamma_i}{2}\right)}\right)^{\frac{m}{2}} \frac{\left[\left(h_*\sin\frac{\gamma_i}{2}+\frac{l}{2}\cos\frac{\gamma_i}{2}\right)^{\frac{m}{2}+1}-\left(\frac{l}{2}\cos\frac{\gamma_i}{2}\right)^{\frac{m}{2}+1}\right]}{\left(\frac{m}{2}+1\right)\sin\frac{\gamma_i}{2}} \tag{8.6}$$

- model of the third degree (II.3)

$$T_i = \frac{A\tau_t^m R_{oi}}{60f^m s_i u^2 n_1}\cdot\left(\frac{\pi(1-\nu^2)l_\Sigma}{EN\left(1-\sin\frac{\gamma_i}{2}\right)}\right)^{\frac{m}{2}}\cdot\int_0^{h_*}\frac{\left(\frac{l}{2}\cos\frac{\gamma_i}{2}+h\sin\frac{\gamma_i}{2}\right)^{\frac{m}{2}}}{R_i - h\cos\delta}dh \tag{8.7}$$

In the above equations assume the following indications:

A, m - dimensionless ratios of frictional strength of the test material in the tribological association and accepted the conditions of the test, c is unknown constant determined by experimental, f — coefficient of sliding friction, $\tau_o = \tau_{\max}$ for $h = 0$ and $x = 0$; $\tau_o = fp(0,0)$, $\tau_t = 0.5\sigma_{0.2}$ is yield stress of the material shear, $\sigma_{0.2}$ is the contractual yield of material tensile strength, $h_* = h \to h_{**}$ is discrete values of wear h_{**} is permissible wear of teeth, γ_i is the vertex angle of the teeth, δ is angle of inclination of plane of the rims to the plane of the cross section of the hole, R_{oi} is rolling radius of the drill rim relative to the rock hole, R_i is the radius of the rim, s_i is the jump between teeth, $u = \omega_2/\omega_1$ is number of gear, $n_1 = \frac{30\omega_1}{\pi}$ is rotational speed of the drill bit,

ω_1 - angular speed of the borer, ω_2 - angular velocity of bit, E, ν - Young's modulus and Poisson number rocks, N - load on the borer, $l_\Sigma = \sum_1^{\tilde{n}_i} l_{ni}$ - the length of the sum of the line of contact of the teeth borer with the rock, l_{ni} - the length of the line of contact of individual teeth, l - the width of the top of the teeth, $\tilde{n}_i$ - the number of teeth on each rim simultaneously in contact with the rock, L_i - sliding friction road of the teeth on the i-th rim per rotation of the borer, $n_i = \frac{2\pi R_i}{s_i}$ - number of teeth per i-th rim.

Carried out an analysis of the impact of both the basic parameters of the process of drilling: axial load action on the drill bit and speed of borehole, on the durability of the work in the drilling hole. The analysis calculation assumes the following values for the parameters of drilling process: axial load $N = 0{,}07; 0{,}14; 0{,}21; 0{,}28 MN$, rotational speed $n_1 = 70; 100; 130; 160 obr/\min$. The calculations were carried out for all combinations of values of parameters. The method first calculated on each rim the average durability $T_i = f(h_*)$ of the roller cone teeth bits in accordance with the accepted forms of models of second and third degree approximations for the developed methods and equations and described: (2), (3). The calculations were permissible wear of $h_{**} = 0{,}01m$. Calculation of durability made for discrete values of wear of the roller cone teeth bits $h_* = 0{,}001; 0{,}002 \ldots 0{,}01m \to h_{**}$. Also according to the other methods is calculated on each rim the average durability $T_i = f(h_*)$ of the roller cone teeth bits in accordance with the accepted forms of models of second and third degree approximations are designed for second and described equations: (6), (7). The calculations were permissible wear of teeth $h_{**} = 0{,}01m$. Calculation of durability made for discrete values of wear of the teeth borer $h_* = 0{,}001; 0{,}002 \ldots 0{,}01m \to h_{**}$. Other data adopted for calculations: tested rock - granite, *l=0,002m, u=1,57, f=0,3,*l_Σ*=0.175m* $\tau_t = 385 MPa$, $E = 2 \cdot 10^4 MPa$, $\nu = 0{,}25$, $A = 1{,}27 \cdot 10^5, c = 1{,}2, m = 1{,}8$.

Design parameters of the tested roller cone are provided in Tab.8.1. The results of numerical solutions of bits durability on extreme rims: I/1 and I/4 was carried out in accordance with the first method based on the model I.2 and the analogue solutions was carried out in accordance with the first method based on the model I.1 and I.3. As for calculations carried out in accordance with use of the first method also it were made the same calculation using the second method based on the models - II.1, II.2 and II.3. In Tables 2 and 3 there are a sample-values of bits durability of the all roller cone rims. Durability was calculated by the model I/3 for extreme drilling parameters. The values of durability are given in hours.

Table 8.1. Parameters of the tricone

cone/rim	$R_{oi}[mm]$	$R_i[mm]$	$n_i[pieces]$	γ_i [deg]	$s_i[mm]$	$l_{ni}[mm]$	$L_i[mm]$
I/1	143	92	20	42	29.7	18	67.42
I/2	103	73	17	44.9	28.3	10	57.24
I/3	65	45	12	43.6	25.7	10	47.30
I/4	17	13	5	41.4	25.4	27	29.86
II/1	145	92	19	42	31.3	13	68.11
II/2	110	80	19	43.8	27.9	12	58.79
II/3	78	55	14	43.7	26.2	10	50.85
II/4	40	28	7	43.3	27.3	10	39.21
III/1	140	90	21	42	28.3	27	66.80
III/2	90	64	16	44	26.5	10	53.98
III/3	55	38	10	44.3	25	10	44.28

Table 8.2. Durability of the bits calculated by the model 1.3 for N = 0,07 MN and n_1 = 70 rev/min

cone/rim	Avarage bits wear [mm]									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
I/1	0,6	1,4	2,4	3,7	5,3	7,2	9,6	12,7	16,5	21,2
I/2	0,6	1,4	2,4	3,6	5,2	7,1	9,5	12,5	16,2	20,9
I/3	0,7	1,6	2,7	4,1	5,8	8,0	10,8	14,3	18,6	24,1
I/4	0,6	1,5	2,6	4,0	5,8	8,2	11,3	15,5	21,0	28,3
II/1	0,6	1,4	2,4	3,6	5,1	6,9	9,3	12,2	15,8	20,4
II/2	0,6	1,4	2,3	3,5	5,0	6,9	9,3	12,2	15,8	20,4
II/3	0,7	1,5	2,6	3,9	5,6	7,7	10,3	13,6	17,7	22,9
II/4	0,7	1,5	2,5	3,9	5,5	7,7	10,4	13,8	18,2	23,7
III/1	0,7	1,5	2,6	3,9	5,5	7,6	10,1	13,3	17,3	22,3
III/2	0,7	1,5	2,5	3,8	5,5	7,5	10,1	13,3	17,3	22,3
III/3	0,7	1,6	2,8	4,3	6,1	8,4	11,3	15,0	19,6	25,4

Table 8.3. Durability of the bits calculated by the model 1.3 for N = 0,28 MN and n_1 = 160 rev/min

cone/rim	*Avarage bits wear [mm]*									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
I/1	0,1	0,2	0,3	0,5	0,7	0,9	1,2	1,6	2,1	2,7
I/2	0,1	0,2	0,3	0,5	0,6	0,9	1,2	1,6	2,0	2,6
I/3	0,1	0,2	0,3	0,5	0,7	1,0	1,4	1,8	2,3	3,0
I/4	0,1	0,2	0,3	0,5	0,7	1,0	1,4	1,9	2,6	3,6
II/1	0,1	0,2	0,3	0,4	0,6	0,9	1,2	1,5	2,0	2,6
II/2	0,1	0,2	0,3	0,4	0,6	0,9	1,2	1,5	2,0	2,6
II/3	0,1	0,2	0,3	0,5	0,7	1,0	1,3	1,7	2,2	2,9
II/4	0,1	0,2	0,3	0,5	0,7	1,0	1,3	1,7	2,3	3,0
III/1	0,1	0,2	0,3	0,5	0,7	1,0	1,3	1,7	2,2	2,8
III/2	0,1	0,2	0,3	0,5	0,7	0,9	1,3	1,7	2,2	2,8
III/3	0,1	0,2	0,4	0,5	0,8	1,1	1,4	1,9	2,5	3,2

The sample results of numerical solution for model I.3 is given in Figure 8.1a, b. The durability was calculated for the whole range of drilling parameters.

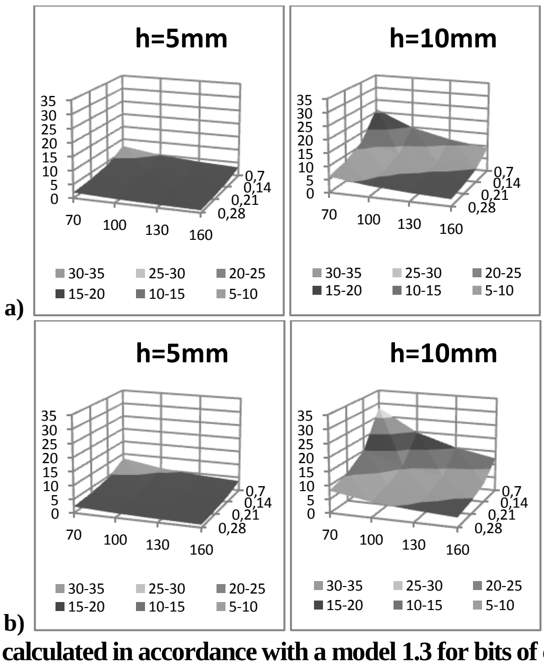


Fig.8.1. Durability calculated in accordance with a model 1.3 for bits of cone number I and held a) to 1 rim (I/1) b) to 4 rim (I/4)

The exact values of bits durability for extreme rims of the first cone (1 and 4) have been calculated by the model 1.3 for extreme drilling parameters N=0,07 MN, n_1=70 rev/min and N=0,28 MN, n_1=160 rev/min and is shown in Figure 8.2.

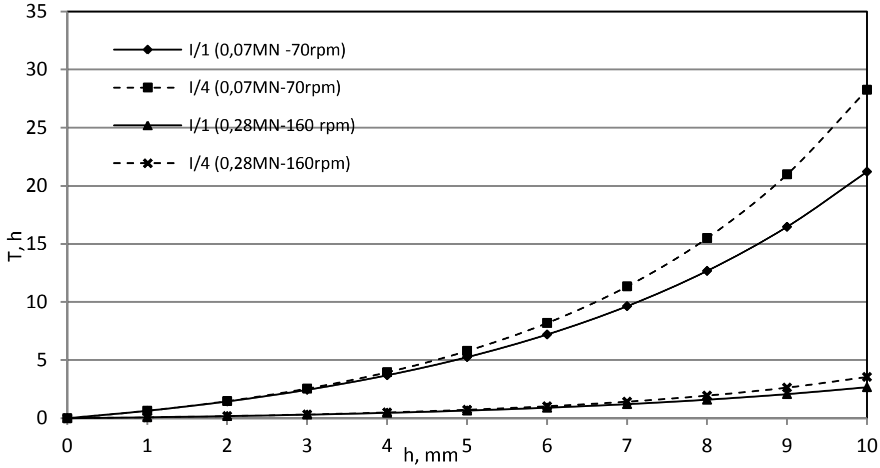


Fig. 8.2. Durability of the bits on extreme 1 and 4 rims for cone I - 1.3 model

However, in Figure 8.3 a, b also includes durability calculated according to the models 1.1 and 1.2 for comparison with the results of durability calculated by the model 1.3.

a)

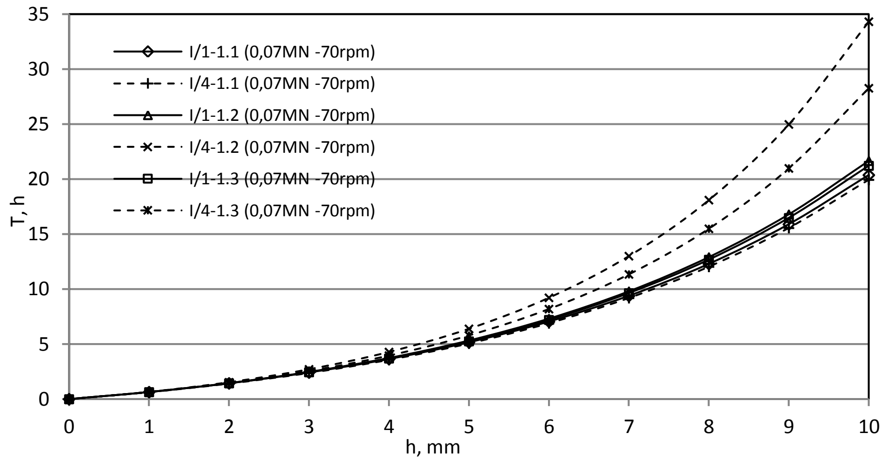


Fig. 8.3. Durability of the bits on extreme 1 and 4 rims for cone I - 1.1, 1.2, 1.3 models: a) minimum drilling parameters, b) maximum drilling parameters

b)

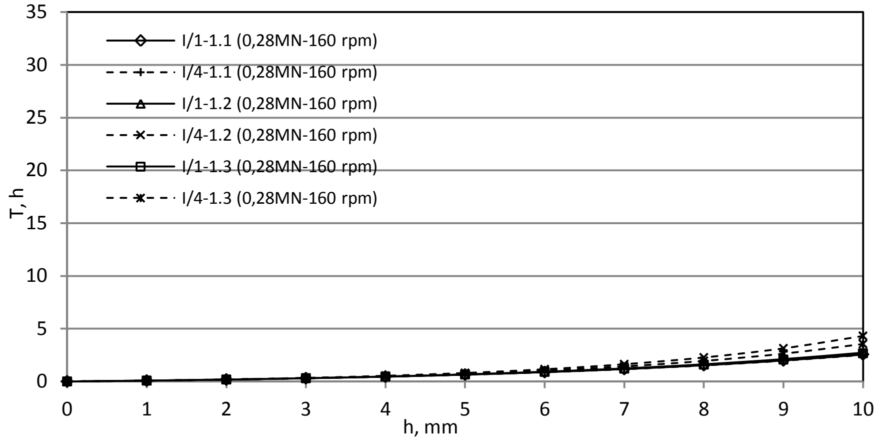
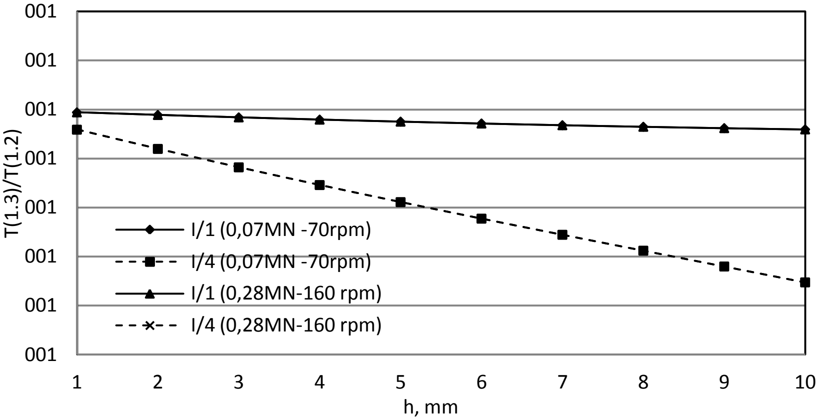


Fig.8.3. Durability of the bits on extreme 1 and 4 rims for cone I - 1.1, 1.2, 1.3 models: a) minimum drilling parameters, b) maximum drilling parameters (con.)

Based on the obtained results it can be seen that there are slight differences in the durability the bits on each cones and rims resulting from the model used for the calculations. The model 1.2 which is a simplified model, durability is always slightly higher than the 1.3 model - the more accurate. Differences durability results (Fig. 8.3a), calculated on the basis of the model 1.2 and 1.3 are the minimum at the rim No.1 - external (solid line) and maximum at the rim No.4 internal (dashed line). They decrease with increasing drilling parameters and the duration of the process (Fig. 8.3b). Durability of the bits calculated by the model 1.1 - which is the simplest of these models - are the smallest.The relative ratio of the extreme rims durability, calculated by models 1.3 and 1.2 ($T_{(1.3)} / T_{(1.2)}$) at extreme drilling parameters does not exceed 0.98 to the rim 1 and 0.82 rim to rim 4 at N = 0,07 MN and n_1 = 70 rpm/min after six hours of work. For N = 0,28 MN and n_1 = 160 rev / min parameters the situation is similar (Fig. 8.4). However, the relative ratio of the extreme rims durability, calculated by models 2.3 and 2.2 ($T_{(2.3)} / T_{(2.2)}$) at extreme drilling parameters does not exceed 0.98 to the rim No.1 and 0.79 to the rim No.4 after six hours of work, and so as for models 1.3 and 1.2. For N = 0,28 MN and n_1 =160 rev / min parameters the situation is similar (Fig.8.4 b). In this case, you will see a noticeable drop in the relative durability of the internal rim No.4.

a)



b)

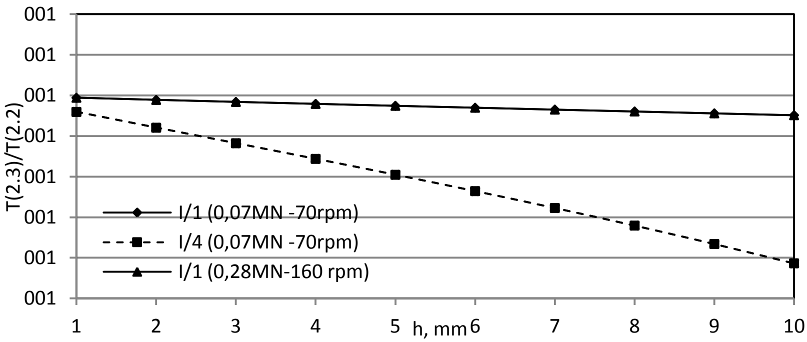


Fig. 8.4. Relative change of bits durability on extreme 1 and 4 rims and extreme drilling parameters

Figure 8.5 shows the relative change of bits durability on the rims 1 and 4 for extreme drilling parameters calculated by methods 1 and 2 for models with the same degree of accuracy, and thus counted: $T_{(1.1)}/T_{(2.1)}, T_{(1.2)}/T_{(2.2)}, T_{(1.3)}/T_{(2.3)}$. At the minimum drilling parameters (N = 0,07 MN and n_1 = 70 rev/min) the relative bits durability of the two extremes rims calculated by: model 1.1 relative to 2.1 shows Fig. 12.5 a. the model 1.2 relative to 2.2 - Fig. 8.5 b, and the 1.3 model relative to the model 2.3 - Fig. 8.5c. These differences deepen over drilling time and reach a maximum of about 30%. At maximum drilling parameters (N = 0,28 MN and n_1=160 rev/min) the situation is similar in the model 1.2 (see Fig.12.5 a), and also for the models 2.2 and 2.3 (Fig. 8.5 b, c).

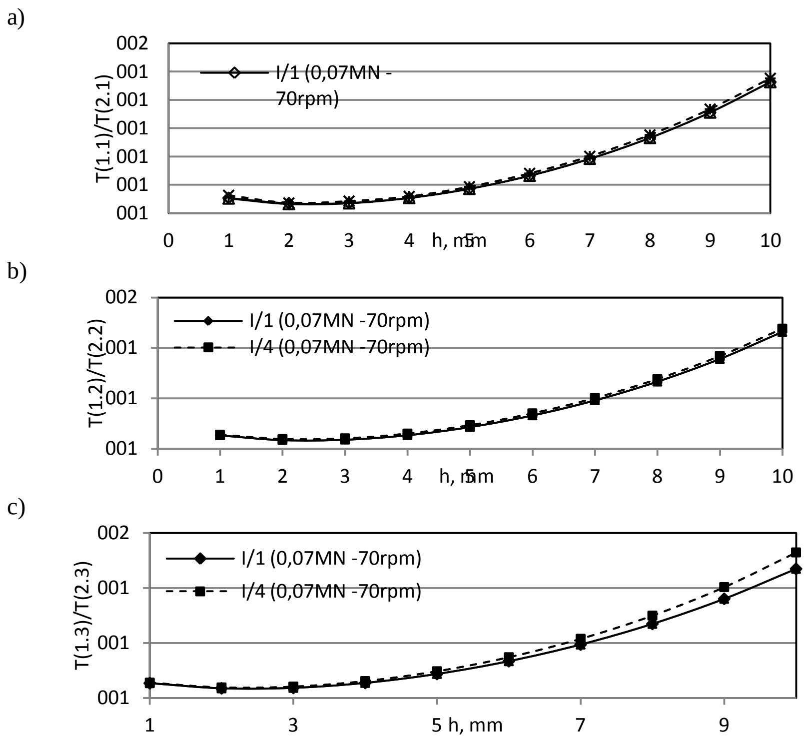


Fig. 8.5. Relative change of bits durability on extreme 1 and 4 rims calculated according to the methods 1 and 2.

Summary

Analysis of the results of numerical solution, as shown in Fig. 8.1 – 8.5 allows you to draw the following conclusions:

1. For the external rims (I/1) the durability calculated by models 1.2 and 1.3 are close to each other . The same fact can be noted in the case of the application in the analysis of models of 2.2 and 2.3.
2. For the internal rims (I/4) durability calculated by the model 1.2 is more than durability calculated on the basis of the model 1.3 over time of drilling These differences are not noticeable when wear is 2mm but grow with the wear of 6 mm. This fact apparently emphasizes the moment achieve by wear its limit, the limit values. The same can be observed in the case of the use of models in 2.2 and 2.3
3. Durability of the external rims I/1 is less than the durability of rims of the internal I/4. External rim needs less time to achieve acceptable wear and as shows the analysis is much more exposed.
4. Disparities arising from the analysis of the durability of the rims of the internal I/4 using models 1.2 and 1.3 and 2.2 and 2.3 tend to apply with detailed analysis of durability, models of third degree approximations 1.3 or 2.3.

Reference

[1] Czerniec M.V. Metoda oceny trwałości uzbrojenia świdrów gryzowych. Fiziko – Chemiczna Mechanika Materiałow, 1991, № 3. - pp. 121-124.
[2] Czerniec M.V., Skvarok J.J. Ocena trwałości uzbrojenia świdrów gryzowych oraz prędkości mechanicznej wiercenia. Problemy Tribologii, 1997, № 3. - pp. 3-10.
[3] Czerniec M., Jaremek P. O zagadnieniu symulacji trwałości uzbrojenia świdrów gryzowych. Problemy Tribologii, 2002, № 2. - pp. 134-139.
[4] Czerniec M.V. Metodologia prognozowania trwałości uzbrojenia świdrów gryzowych. Problemy Tribologii, 2002, № 4. - pp. 107-113.
[5] Czerniec M., Jaremek P. Analiza matematyczna zużycia uzbrojenia świdrów gryzowych. V Konferencja Naukowo-Techniczna nt. „Zagadnienia dydaktyczne w środowisku systemów technologicznych". Kazimierz Dolny n/Wisłą 5 - 6.06.2003.
[6] Czerniec M., Jaremek P. Analiza wpływu nacisku osiowego na zużycie uzbrojenia świdrów gryzowych. Eksploatacja i niezawodność, 2004, № 4(24). - pp. 73 – 78.
[7] Jaremek P. Analysis of the effect of the parameters of drilling on the durability arms of drill bits. The third chapter of a monograph - "Informatics methods as tools to solve industrial problems". Edited by Jerzy Lipski, Antoni Świć, Agnieszka Bojanowska. Wyd. PL, Lublin 2012.

COMPERATIVE ANALYSIS OF METHODS FOR ASSESSING THE DURABILITY OF ROLLER CONES BITS

Summary

This paper presents the results of a comparative analysis of roller cones bits durability which the calculation was based on the wear patterns of these elements in the drilling process. Wear patterns are based on well-known study of the kinetics of tribological contact in sliding friction. The computational analysis of relative durability was performed, and the results are shown in graphical form.

Keywords: drilling, roller cone, durability, wear

ANALIZA PORÓWNAWCZA METOD OCENY TRWAŁOŚCI ELEMENTÓW UZBROJENIA ŚWIDRÓW GRYZOWYCH

Streszczenie

W artykule przedstawiono wyniki analizy porównawczej trwałości uzbrojenia świdrów gryzowych, której obliczenia przeprowadzono w oparciu o modele zużycia tych elementów w procesie wiercenia. Modele zużycia bazują na znanym podejściu badania kinetyki kontaktu tribologicznego przy tarciu ślizgowym. Przeprowadzono analizę obliczeniową względnej trwałości, a wyniki podano w postaci graficznej.

Słowa kluczowe: wiertnictwo, świder gryzowy, trwałość, zużycie

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9. Computer-aided design of human knee implant

With the development of science and technology has evolved considerably modern medicine. Nowadays, doctors have a lot of modern, complex and specialized tools that help save lives. This rapid growth is due to the cooperation of doctors and engineers together exchanging experiences.

An example of the application of advanced technologies in medicine is joint replacement. In short, it is a treatment designed to eliminate the affected joint (or part thereof), and inserting an artificial element that takes over its function [8] The reason why is used as advanced treatment, there are many degenerative diseases that destroy the anatomical structure of the joint and impair its functionality at the same time. Arthroplasty is a method mainly used for hip and knee. Thanks to the efficiency of patients is restored limbs, which affects significantly improve their well-being. In the present work focuses on the replacement of the knee, which is one of the most busy and complex joints.

Structure and physiology of the human body is very complex and involves a number of problems posed designers. Replacement of a natural element requires knowledge of anatomy artificial and processes in the human body. In addition, knowledge is needed about the materials acceptable by the body that will not rapidly degraded and destroyed. Another problem is the variety. Each person is different and has different parameters of the knee joint. Therefore, these issues must be taken into account during the construction of the prosthesis.

Currently on the market there are many models of implants used in the treatment and presented in the work of the project is to realize the complexity of the process of constructing this type of implant and present problems arising from the anatomy and physiology of the human body.

9.1. Human knee structure

The main task of the knee is a combination of three bones: the femur, tibia and fibula. The knee is the joint that transmits traffic load between these elements. Shape of the articular surfaces and the range of motion depends on the number of degrees of freedom, as well as the loads that occur in the pond. The knee is structurally very complex and extensive. Here, in Figure 9.1. shown right knee in extension.

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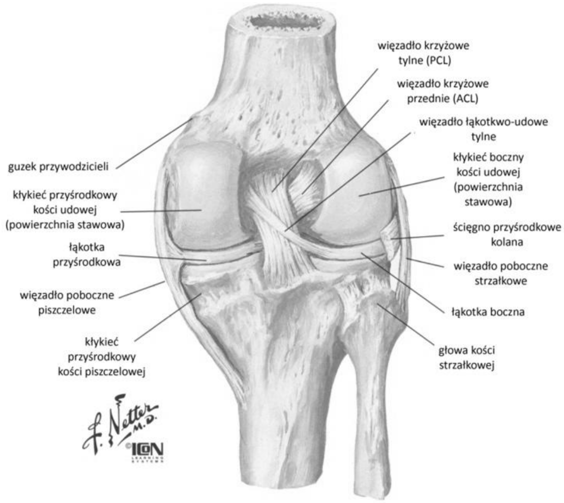


Fig. 9.1. Right knee in extension [7]

In the picture above you can identify the femur, tibia and fibula thinnest. In addition, the articular surfaces are marked with both condyles and the various ligaments. Anterior cruciate ligament (ACL) and ACL rear (PCL) closely connect the femur and tibia. During rotation of the bent knee ligaments that wrap around each other. Stabilize the joint in the transverse direction provide collateral ligaments: tibial and peroneal. The main work is done when the knee is straight, joint rigidity to the whole [1, 7].

Figure 9.2. shown right knee in flexion, showing clearly the articular surfaces of the femur.

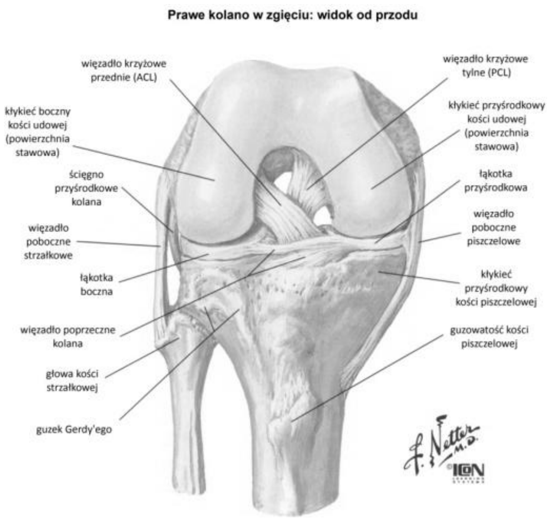


Fig. 9.2. Left knee in flexion [7]

The picture shows that the lower part of the femoral condyles are two: lateral and medial. The tibia and the finished bush is, however, used in medicine to determine the condyles. Articular cartilage that covers the knuckles of the femur and tibia, is designed to provide lossless sliding movement and protect the knee joint from the small overloads.

9.2. Biomechanics of human knee

In theory, the knee joint has six degrees of freedom. Three degrees of freedom are rotational motion while the other refers to the progressive movement. Movements offset by Jakob disease are as follows [8]:

- In the anterior – posterior direction,
- In the medial – lateral direction,
- Compression – distraction.

Rotational movements of the knee relative to the axes are [8]:

- straightening – bending,
- adduction – abduction,
- internal rotation - external.

The above description perfectly illustrates and helps you understand the figure 9.3.

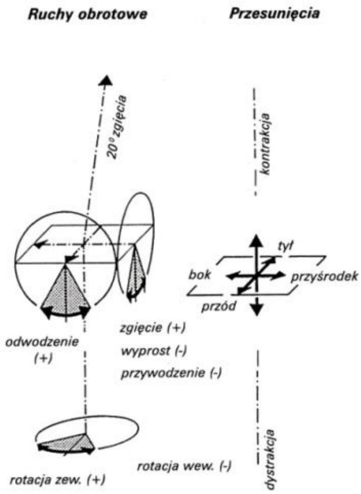


Fig. 9.3. Degrees of freedom of the knee by Jakob [8]

It is important that most of the degrees of freedom eliminated each other, or is limited by the muscles and tendons. As a result, it can be concluded that the knee joint has one degree of freedom [1]. This is the most important movement of flexion and extension. Alternatively, when the knee is flexed, there is a possibility of rotation relative to the longitudinal axis – when there is possible a second degree of freedom.

This approach is also in the theory of mechanisms and manipulators. The knee joint is treated as a biokinematic pair of class V with one degree of freedom, or a biokinematic pair of Class IV with two degrees of freedom. Figure 9.4. shows examples of patterns multibody models of the human body including the connections, which is the knee joint.

The range of motion of the knee is described by angles. In the case of extension and flexion, respectively angles are 10^0 – 0^0 – 145^0, where the angle of 0^0 corresponds to knee in extension. In the case of the bent knee internal rotation is 15^0, and 35^0 external rotation [8]. Kettelkamp described the range of motion in the case of activities performed in daily life:

- walk 0^0 – 67^0,
- sitting 0^0 – 93^0,
- climbing stairs 00-900.

The knee joint has to move large, and also a variety of loads. The values of these loads are highest compared to other bone and joint connections. Analyzed pond connects three bones: femur, tibia and fibula. In addition, there is a pond kneecap.

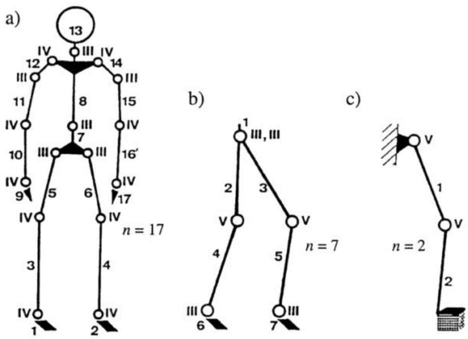


Fig. 9.4. Structural schemas of selected human body parts [5]

The knee joint has to move large, and also a variety of loads. The values of these loads are highest compared to other bone and joint connections. Analyzed knee-joint connects three bones: femur, tibia and fibula. In addition, there is a kneecap. On the knee influence of internal muscles forces and external forces. An example of an external force may be the force of gravity. Are also important: the weight of the human body, the force acting on the muscle, and the value of each of the angles between the body axes. Strains occurring in the knee can exceed several times the body weight. What's more, the forces and torques can act in different directions. Knowledge of the biomechanics knee is still being developed and confirmed by numerous experiments. With the development of the knowledge were created many models describing the biomechanics of both traffic and load. Created models usually refer to common tasks performed by humans. The dominant scheme of the knee loads is Maqueta model, shown in Figure 9.5.

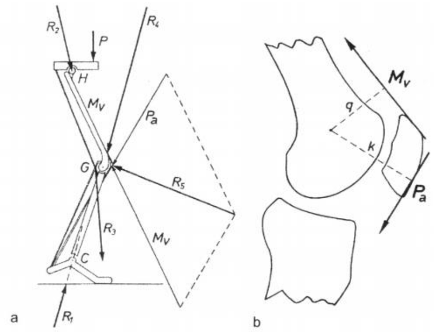


Fig. 9.5. Knee loads model by Maqueta proposed [1]

While standing on both legs knees are loaded about 85% by whole body weight. This is due to the fact that the load does not include the legs below the knees. Thus, for a person weighing 70 kg knee joint will be charged to the force of 292N. On the other hand, in the case of standing on one leg joint will be load about 93% of body weight. This situation, together with a description of the forces shown in the figure below. Identification of individual forces [1]:

R – resultant loads of body weight,
L – burdens resulting from the impact of ilio-tibial band,
a, b – arms of subsequent forces,
O1, O2 –curvatures center of condyles.

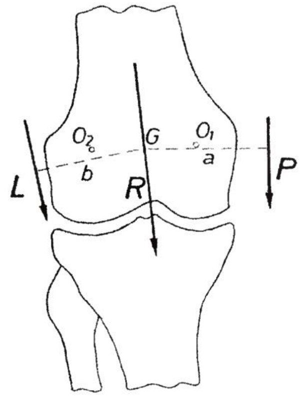


Fig. 9.6. Loads knees while standing on one leg [1]

Another important question is fact that the condyles are not charged uniformly as previously thought. Studies have shown that 70% of the load during walk carries medial condyle and the remaining value - lateral. Taking into account this fact allows better knee prosthesis design and prevent excessive and accelerated wear. In addition, the knee joint is subjected to large bending moments. Despite the fact that the forces during walk are small, the distance between the knee and heel are significant.

Human knee joint is the most complicated, both in construction and operation, in relation to the other connections between the bones. On the knee anatomy consists of a number of bone tissue and soft tissue such as ligaments and tendons. Each tissue has a specific function and is necessary for the proper functioning of the joint. For the production of lubricating element is responsible synovial bursa. Produced synovial fluid may adjust their viscosity properties to the situation, which cannot any lubricant or oil produced artificially by man. External cartilage of the femur and tibia are incredibly smooth. The whole creates a harmonious mechanism that hard to replace the artificial creation.

9.5. Knee joint prosthesis

The first attempts to restore partial performance of patients with chronic illnesses of knee joints take place already in the nineteenth century. The pioneer in this field was Ferguson. In 1861 he removed the outer surfaces of the knee joint so that the motion was made at the surfaces occurring under cartilage. Unfortunately, after several treatments, it was found that this method is inefficient. Side effects were completely arthrodesis by fusion of the femur and tibia or knee high instability, which led to the injuries. Two years later, in 1863, Verneuli performed a similar operation but applied interpositor. Interpositor called the element that was inserted between the cut ends of the joint. Initially used natural materials such as adipose tissue, medial bursa, joint capsule, skin and muscles. Then started implementation artificial interpositor such as glass, nylon, bakelite. This method was also ineffective [185]. Almost a hundred years later, in the years 1938-1940, Smith-Petersen, Campbell and Boyd presented the works in which metal parts are used to replace joint surfaces of the femur or tibia. Their work was a fundamental contribution, and on this basis formed the first internal knee prosthesis called endoprosthesis. Modern joint replacement was initiated by Charnley in 1962 he created the hip implant using a metal part of the femur and the acetabular polyethylene. To connect with bone implant bone cement was used. The idea of such a solution moved and adopted into the knee joint Canadian Gunston in 1971. Range the prosthesis mobility was limited, however, when compared with previous attempts at this method gave much better results. An example of the first generation prosthesis is shown in Figure 9.7.

In 1974 there was the first international conference on the knee prosthesis. It was attended by engineers and surgeons. During this meeting adopted the basic principles to be followed while inserting dentures. The types of prostheses were divided into two categories: the hinge and runs – slip. With the development of knowledge about the biomechanics of the knee, as well as the results of clinical experience in the eighties was established the second generation of knee prostheses [8]. Here, the picture a second-generation prosthesis the Geometric type.

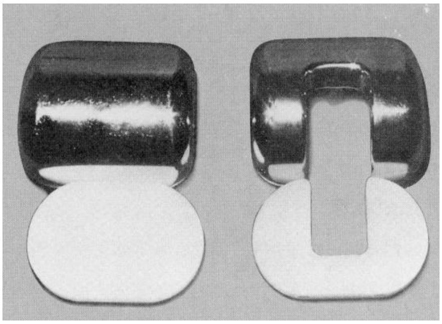


Fig. 9.7. First generation prosthesis [8]

In 1974 there was the first international conference on the knee prosthesis. It was attended by engineers and surgeons. During this meeting adopted the basic principles to be followed while inserting dentures. The types of prostheses were divided into two categories: the hinge and runs – slip. With the development of knowledge about the biomechanics of the knee, as well as the results of clinical experience in the eighties was established the second generation of knee prostheses [8]. Here, the picture a second-generation prosthesis the Geometric type.

In 1999 was the second international conference in London, which lists the experience gained. Currently still research is being conducted and the development of knee arthroplasty. Patients who are implanted knee implant, have an efficiency of close to natural. Can perform most of the basic activities and function normally [8]. Different types of prostheses archive is shown in Figure 9.9.

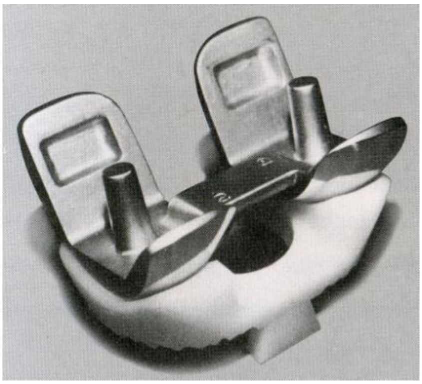


Fig. 9.8. Second-generation prosthesis [8]

Fig. 9.9. Prosthesis [8]

9.6. Classification of knee prostheses types

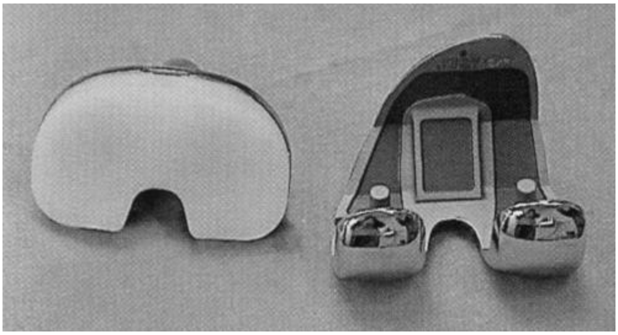
Depending on the design, universal prosthesis can be formed on either right or left knee. Components fixed to the tibia may occur in different versions. For example, the metal part and the polyethylene insert can be permanently connected to or constitute separate elements. Classification of implants used due to differences in mounting system and the shape of various parts of the prosthesis. You can also take into account the movement degree of freedom of a new joint, an area of joint surface replacement and dependence of the extent of the degree of cutting-off posterior cruciate ligament.

The first classification refers to the area of joint replacement. It is not always necessary to replace the whole, in some cases, a partial denture. Therefore distinguished [2]:

- One-section prosthesis used in situations that require the replacement of the damaged compartment side or medial. The remainder of joint surfaces is not damaged and does not require any interference. Especially elderly patients suffering from one-section arthritis, so this solution is best for them.
- Two-section prosthesis, this prosthesis were the first generation. Today, they are no longer used.
- Three-section prosthesis – they are used most frequently. They include replacement all of the knee joint also with the kneecap.

Another classification of implants is the degree of free movement of the joint. The anatomy of the knee indicates that part of freedom degree are taken away by the tendons and ligaments. During surgery, some of these connections must be removed. This is due to the severity of the disease. Therefore classified [8]:

- not related prosthesis surfaces which are not connected to each other in a sustainable manner, for example hinges. However, this does not mean that they do not limit some moves in different axes of the joint. Prosthesis of this type is shown in Figure 9.10, showing clearly the absence of any connection between the surface of the plastic bursa and metal head,



9.10. Not related prosthesis [8]

– partly related prosthesis, which are the largest group. They are used in advanced cases of joint disease and significant changes in the physiology of the knee. The purpose of this type of solution is to limit the range of motion in a large or small extent in order to maintain the stability of the joint. In another case, could lead to the creation of large clearances and accelerated wear prosthesis surface. Below shows the one of the types this solution,

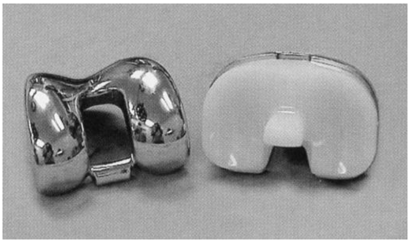


Fig. 9.11. Not related prosthesis [8]

– the last type of prosthesis classified according to this criterion are fully related prosthesis. In addition, they can be divided into the hinge, hinge rotation and hingeless. Their function is similar to the existing partial prosthesis, to limit the movement in several planes. Solutions of this type are used in a very extensive destruction of the knee joint and reduced functionality of side ligament. Implants of this type is shown in Fig. 9.12.

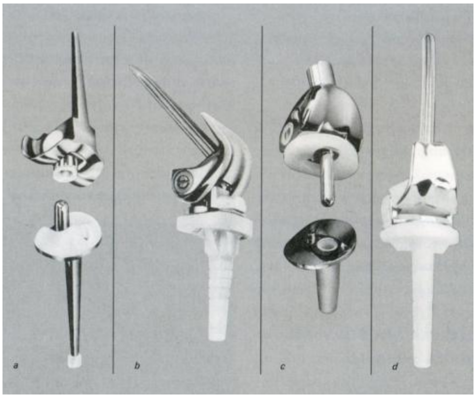


Fig. 9.12. Fully related prosthesis [8]

9.6. Knee joint prosthesis project

To projecting were used advanced engineering software from the family of CAD (computer aided design), which allows for the creation of three-dimensional elements of the knee joint bones and individual elements of the prosthesis. In addition, were used the CAE (Computer Aided Engineering) software to implant strength calculations. Therefore used the following programs: Materialise MIMICS, Catia and Abaqus.

Materialise Mimics

Materialise Mimisc allows you to processing and editing 2D images taken by computed tomography CT or magnetic resonance imaging MRI to create three-dimensional models with very high accuracy. It is also possible to make accurate measurements of the bones, tissues and organs. Created three-dimensional models can be exported to many engineering programs in compliance with all dimensions and material properties. In Figure 9.13 shows the main window program. A characteristic feature of this software is to divide the screen into four main views: coronal, axial, sagittal, 3D. The first view is interpreted as a projection of the front, the other as a top, and the third as the throw from the right side. The last window is responsible for the display of three-dimensional models.

Each photo also has a number and coordinates. The menu includes a variety of tools used for editing images, as well as to generate three-dimensional models. An important tool is the "windowing", which allows you to adjust the grayscale image scanner according to the scale Hounsfield'a. With this scale, you can distinguish soft tissue from the bone. This tool greatly affect the work and makes it easy to edit various slices. More of the same in the radiology literature [3, 4].

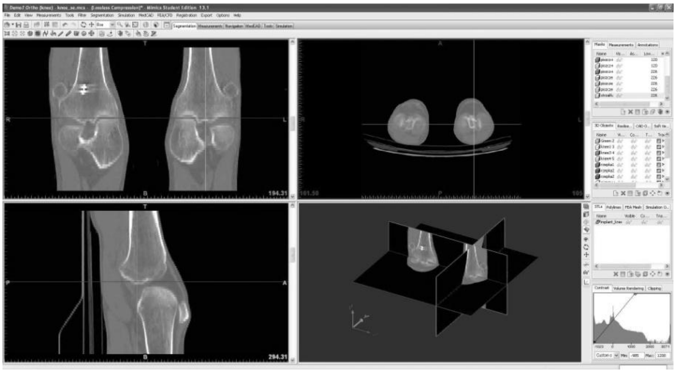


Fig. 9.13. Mimics window

Catia

Catia is an integrated CAD / CAM / FEM system. This software is used in automotive, aerospace, engineering and many other fields [2]. In this work program was used to edit and create three-dimensional models of the knee bone, as well as all elements of the prosthesis. Catia has many modules that allow you to solve various engineering problems. The study was based following modules:

- *Part design* – creating and part edition,
- *Generative shape design* – creation of complex models with the surface engineering,
- *Assembly design* – tool for numerical assembling.

Abaqus

Abaqus is the advance CAE engineering tool. Its use is mainly the analysis of systems, using the finite elements method (FEM). In the industry, this program is used to resolve issues related to the mechanics of solids and fluids, on the strength of machines and structures, taking into account many factors such as load, temperature, electrical conductivity, etc [296]. In this work, the Abaqus was used to analyze strength designed knee prosthesis. To perform a knee prosthesis model, are necessary three-dimensional models of bones found in the joint. To create such models were used Materialise MIMICS and Catia programs. The starting point for the creation of these models were two-dimensional CT images. The work result of the Mimics program was to obtain surface models of all bones of the knee. Created a three-dimensional surface model was then exported to the file "iges". This allows you to open it in a program such as Catia. All the models are in one assembly as shown in Figure 9.14.

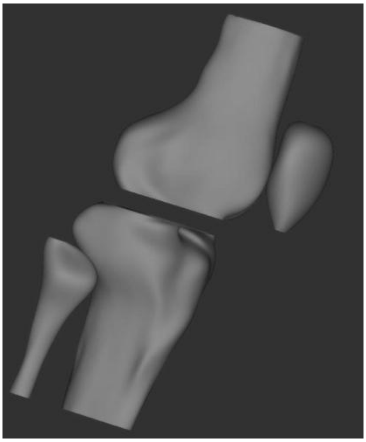


Fig. 9.14. Surface models of all the bones of the knee

Surface models created in MIMICS need to be refined – namely, completing the missing space and convert closed surface into editable block. For this purpose, was used the Catia software and Generative Shape Design module. Figure 9.15 shows the surface model that was loaded and edited in Catia, so that roughly resembled normal bone knee.

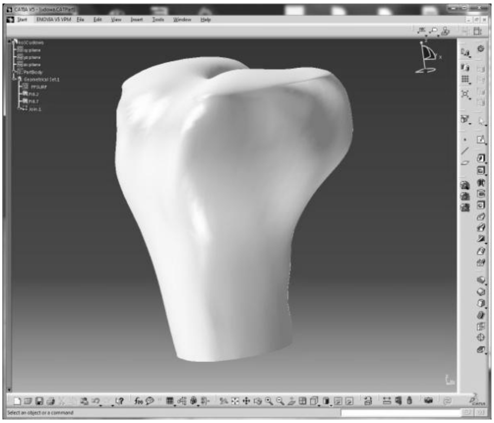


Fig. 9.15. Knee solid model

Every bone exported from the Mimics required adjustment. Therefore benefited from the various functions of Catia: connecting, notching and filler to fill the gaps and create a closed space. Solid models were created using the function Close Surface. This can be easily edited. It has also made a full assembling of the knee with solid elements, which is shown in Figure 9.16.

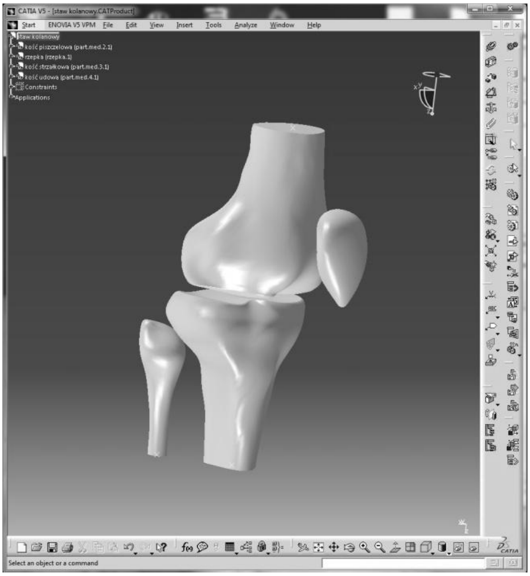


Fig. 9.16. Knee joint assembling

Thus prepared three-dimensional models were used to perform knee replacement components. It is important that all the dimensions of the bones have been preserved. In addition, the entire assembly also preserves the appropriate distance between the solid elements. This allows for faster and more efficient prosthesis modeling.

Further work aimed at designing the components of the knee prosthesis and preparation of bone models to adequately trimed to prosthesis project. As a result, was made the assembling of knee joint – prosthesis. In the assembly includes the need to not change distance between the femur and tibia. Otherwise, it could result in shortening or lengthening of the lower limb, increased tension of soft-tissue and other complications. Submission of the final result is shown in Figure 9.17.

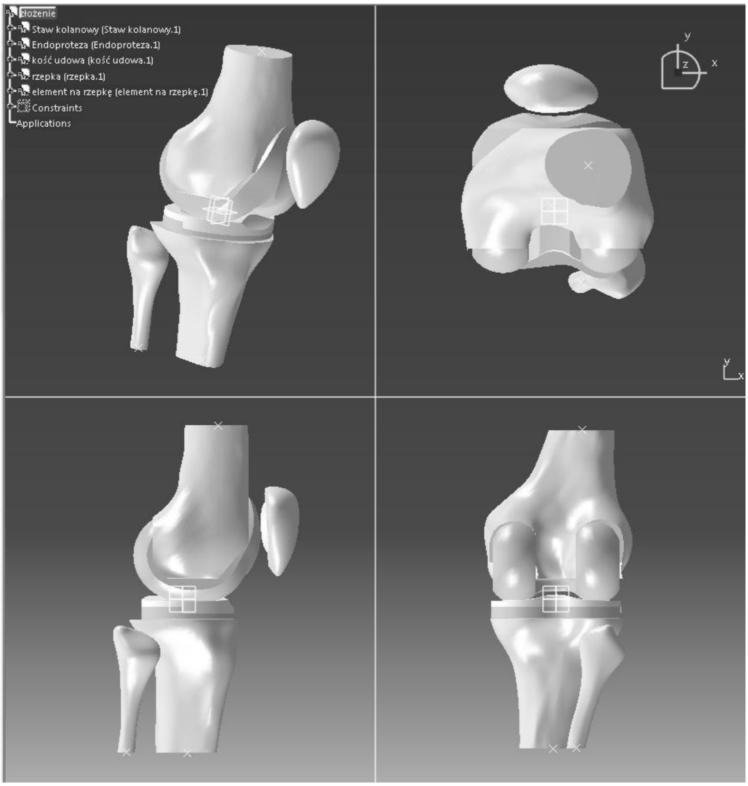


Fig. 9.17. Final result

The final stage of the design was to make the material strength of numerical simulations designed implant components. Below are presented the analysis of the strength of one of the components of prosthesis - polyethylene liner, which acts as the role of the ligament in the assembly. In this paper, the polyethylene component uses high density polyethylene UHMWPE 1000 produced by "Zatorski" [9]. This biomaterial is used to make various types of implant components. Table 9.1. presents selected physico-chemical properties of the material.

Tab. 9.1 [9]

Properties	**Unit**	**Value**
Density	g/cm^3	0,93
Stress at break	MPa	>18
Elongation at break	%	17
Flexural strength	MPa	>700
Impact strength	kJ/m^2	Does not crack
SHORE hardness	-	63
Friction coefficient	μ	0,19
Grindability	μ /km	0,45

After preparing the data for the program are generated Abaqus finite element mesh polygons. The last step is to create a model preparation Mesh on each part. This is an important step and, depending on the density of the grid depends on the accuracy of the results. Due to of the complicated geometry were selected mesh consisting of triangles. Polyethylene element as the most vulnerable to destruction was covered with the densest mesh (fig. 9.18).

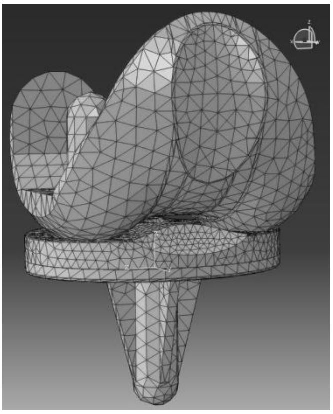


Fig. 9.18. FEM mesh

Aggregated load tested elements have been taken on the basis of knee mechanical calculations for the person weighing 70 kg. To the analysis were assumed force F=3000N. After these operations have been carried out numerical calculations of deformations and displacements of investigated objects. The results of calculations made by the computer are only an approximation of the real. Therefore you should not rely solely on them. On the other hand, this approximation is accurate and defines a basis for further research and analysis. Based on data taken from the literature and databases resulting from the analysis of the finite element method, it was found that the most vulnerable to damage component is polyethylene liner. Therefore, most attention was paid to this element. The analysis was carried out for three dimensional versions of the polyethylene liner, and for each calculation performed. Made models differed among themselves medial-lateral radius. Therefore, each of the models was subjected to a separate analysis. In addition, high-density polyethylene strength does not exceed 18 MPa. The value of the applied force is 3000N – so this is an extreme case.

Below are drawing showing distribution of reduced stress and reduced contacts the polyethylene liner.

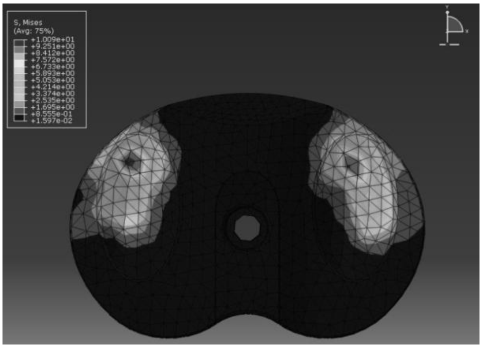


Fig. 9.19. Reduced stress of polyethylene pad radius R = 17 mm

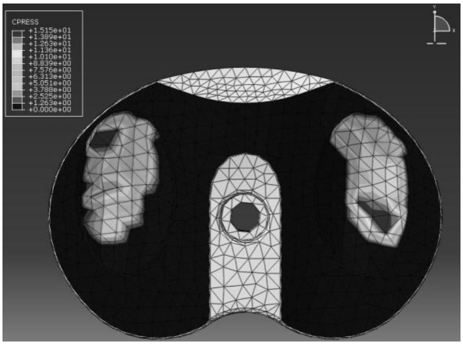


Fig. 9.20. Polyethylene contact stress pad of radius R = 18.5 mm

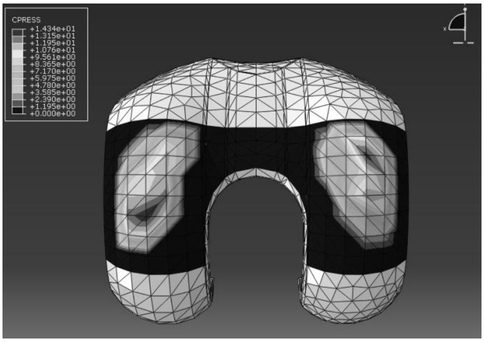


Fig. 9.21. Pressures established on the femur of the model R18, 5

Conclusions

Modern medicine allows you to exchange the damaged structure of the human body to artificially produced element. Treatment of this type owe the amazing progress of science, technology and medicine. What was once considered science fiction, now becoming a reality. Arthroplasty is an example of the application of modern methods of treatment. It is important that these methods are effective and long-lasting. Strength created and implanted implants are counting in the years. They must not of course fully replace natural tissues. Artificial components are unable to regenerate, as is the case with full biological structures. Significant is the fact that this method of treatment has been successful and can be repeatedly used [1, 3, 4]. Human knee joint is a complex combination of cooperating bones. It consists of a number of bone tissue and soft tissue, and each of them full of functions and is essential for the proper functioning of the knee. Biomechanics of the joint is also an intricate issue. The forces acting on the knee can exceed several times the mass of the human body. The knee joint has to be resist by a strong stress and additionally dampen any vibrations.

Creating a prosthesis model for this study consisted of four main stages. The first step was to create a three-dimensional solid models of bones of the knee joint based on images from computed tomography. For this purpose, Materialise MIMICS software and created surface models of the bones. Then, these models were finished and set up a full assembling of the knee using Catia software.

The second step was to create a prosthesis elements including shape and dimensions of the previously created model of the knee. As the shape of the bone is very complex, this step continued the longest. The various components of the endoprosthesis is based on data taken from literature [2, 8]. Finally, the model consists of the following elements: metal base, polyethylene liner, femoral part, element fixed to the kneecap and the fixing screw.

The next step is the selection of appropriate biomaterials, analysis of the mechanical properties of materials and the creation of models in the Abaqus software. Then prepared previously created prosthesis elements to the stress analysis. Given adequate forces, defined anchoring and prepared contacts.

The last step is to perform calculations and finite element analysis. With three different models proved to be the most robust model of R18,5. Static analysis showed that reduced stress and pressures do not exceed the limits. The weakest element of each model proved to be a polyethylene liner. This is of course related to the biomaterial used to produce it.

Perhaps, however, this model would require a better fit geometry and extended stress analysis so that it can be put into production. In addition, the creation of the endoprosthesis is just the beginning. It would be to design a number of important tools, used by doctors during the process of implantation. Without them, this process would be very difficult or impossible to carry out.

References

[1] Będziński R.: *Biomechanika inżynierska*, Wrocław 1997.

[2] Czerwiński E., Chrzan R.: *Współczesne techniki obrazowania osteoporozy*. Twój Magazyn Medyczny. Osteoporoza II, 8/2005, rok X, 8(157); pp. 7-16.

[3] Deffner R. H.: *Clinical Radiology The Essentials*, Baltimore 2007.

[4] Gunderman R.B.: *Essential Radiology*, New York 2006.

[5] Kędzior K., Knapczyk J., Morecki A.: *Teoria mechanizmów i manipulatorów*, Warszawa 2002.

[6] Kowalewski P.: *Modelowanie tarcia w endoprotezie stawu kolanowego*, Wrocław 2007.

[7] Thompson J. C.: Atlas anatomii ortopedycznej Nettera, Wrocław 2007. 168

[8] Vagas, M. - Hajduk, M. - Semjon, J. - Páchniková, L. - Jánoš, R.: *The view to the current state of robotics* .In: Advanced Materials Research. Vol. 463-464 (2012), p. 1711-1714. ISSN 1022-6680

[9] Wicki J, i inni:. *Assessing clinical probability of pulmonary embolism in the emergency ward: a simple score*. Wyd. Arch. Intern. Med. 2001 161:92–7.

[10] Strona Głowna firmy Zatorski, http://www.zatorski.pl/ [dostęp 12.06.2012] 295

[11] http://www.kim.pllub.pl [dostęp 21.06.2012]

Komputerowe wspomaganie projektowania protezy stawu kolanowego człowieka

Streszczenie: W pracy przedstawiono proces projektowania endoprotezy stawu kolanowego człowieka. Do zaprojektowania wykorzystane zostały zdjęcia CT pochodzące z rzeczywistych badań klinicznych. Do wykonania modelu 3D ze zdjęć CT wykorzystano program Materialise Mimics. Na podstawie tak otrzymanego modelu przeprowadzono dalsze prace w celu otrzymania modelu STL niezbędnego do przeprowadzenia badań numerycznych metodą elementów skończonych. W pracy przedstawiono wyniki badań numerycznych tylko dla jednego elementu jakim jest wkładka z polietylenu medycznego, która będzie pełniła rolę łękotki w protezie.
Słowa kluczowe: proteza, staw kolanowy, MES, CT, modelowanie 3D

Computer-aided design of human knee implant

Abstract: This paper presents the design process of human knee implant. The design has been used CT scans from the actual clinical trials. To make a 3D model from CT images Materialise Mimics software was used. On the basis of the resulting model, further work was carried out to obtain a STL model is necessary to carry out research numerical finite element method. This paper presents the results of numerical only one element of which is the medical polyethylene insert, which will act as a prosthetic meniscus.
Key word: implant, human knee, FEM, CT, 3D modeling

*MIKULAS HAJDUK**
*FRANTISEK DUROVSKY***

10. NFC technology and automation applications

Introduction

Near Field Communication (NFC) is a new smartphone trend coming up to scene during last two years. NFC brings new interesting possibilities to mobile devices not only in the field of wireless payments. Even though the technology already exists, the necessary infrastructure and supporting devices still have some way to go. This article describes the potential and benefits of this new technology for industrial and automation applications.

10.1. Current wireless technologies

Thanks to constant development, wireless technologies became very widespread and commonly used even in areas, where their employment was recently hardly imaginable.

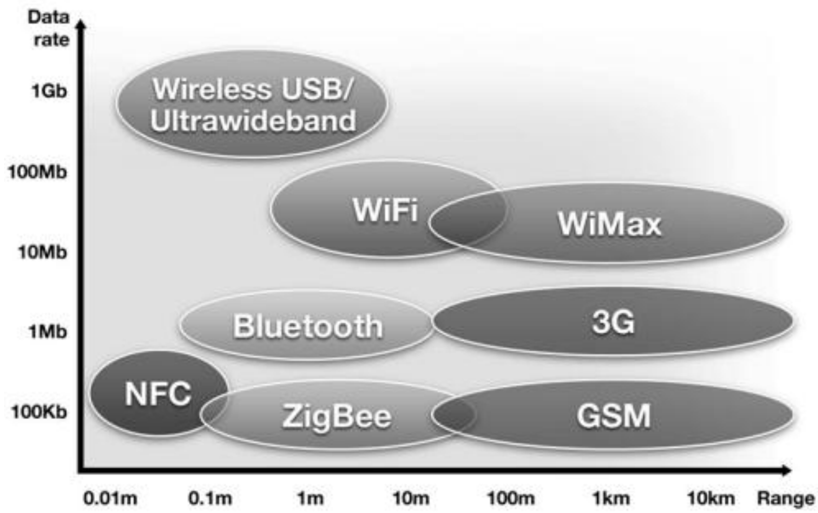


Fig. 10.1. Overview of current wireless technologies [1]

The progress done in the field of wireless technologies during the last two decades has brought results of laboratory tests to the pockets of common people.

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While the 90's where characteristic by expansion of mobile phones and the last decade was dedicated to smartphones and wireless internet and multimedia, current development is focused not only on increasing transmission speeds, interconnecting various devices and expanding the range of Wi-Fi transmitters, but on gradual replacing of remaining signal and power cables by wireless transmission as well. WiTriCity and QI standards using magnetic resonance currently serve mainly for wireless recharging of mobile devices, however, considering the growing electro mobile market, there is a great potential of further raise.

In terms of data transmission it is possible to say that currently available technologies cover a wide spectrum of applications from simple RFID contactless card reading by speed of hundreds of bits per second, over standard Bluetooth and Wi-Fi up to high-speed WI GIG technologies with data rates up to 7 Gb/s coming soon for use in mobile devices.

Tab. 10.1. Overview of several wireless technologies

	ZigBee	**Wi-Fi**	**Bluetooth**	**UWB**	**NFC**
Data Rate	20,40,250 kb/s	11-54 Mbit/s	1Mbit/s	100-500 Mbit/s	425kbit/s
Range	10-100m	50-100m	10m	<10m	<20cm
Networking	Ad-hoc, peer to peer. star, mesh	Point to hub	Ad-hoc, very small networks	Point to point	Peer to peer
Operating frequency	2.4GHz worldwide	2,4 and 5 GHz	2.4GHz	3.1-10.6 GHz	13.56 MHz
Power consumption	Very low	High	High	Medium	Low

In addition to spheres such as multimedia, internet and voice transmission, wireless technologies become frequently used in industry as well. The main reasons for industrial use:

- higher reliability
- extended control possibilities
- cost savings

The ratio of a sensor/wiring costs has recently changed so dramatically, that in case that there are no time control critical processes, it is possible to save up to 70% of expenses by using wireless technologies compared to standard wiring solutions. Thanks to the employment of wireless technologies the realization of many applications becomes economically preferable, whilst expansion of already existing networks is rather simple considering used communication standards.

10.3. RFID technology

RFID which stands for *Radio frequency identification* has been a common part of our everyday life for many years. ID cards, last generation of credit cards, car keys, antitheft store protection, logistics, highway tool systems and even animal electronic identification is based on RFID chips.

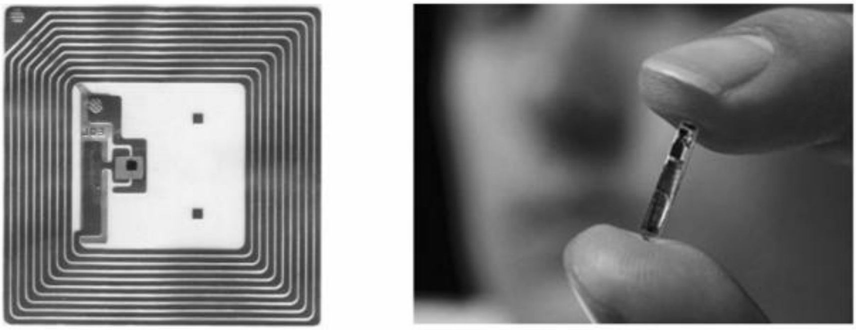

Fig. 10.2. Types of RFID chips

RFID uses electromagnetic induction as basic communication transmission method, in contrast with other well known wireless technologies such as Wi-Fi, Bluetooth, 3G, etc, using radio transmission principle.

RFID reader emits electromagnetic waves, which are the main source of energy for miniature capacitor in passive circuit. Charged capacitor supplies communication chip by energy, necessary for data transmission. The capacity of RFID chip is usually dozens, the most hundreds of bytes and maximal distance between reader and chip is up to 5 meters (highway toll systems)

10.4. NFC – Near field communication

Whilst RFID technology is primarily designed for simple wireless read of small data size, NFC technology due to active module implementation mostly in smartphones, pushes the use of electromagnetic induction in wireless communications more further.

The possibility of reading passive circuit information, so called NFC tags is broadening by another two very interesting options:

- *Emulation of Credit card*
- *Peer to peer communication*

Many modern smartphones provide NFC connectivity even today and analysts expect its 50% coverage within all active devices until end of year 2014 (See Fig. 10.3). There is a high probability that in combination with Credit card emulation, NFC will assume the role of main wireless payment medium.

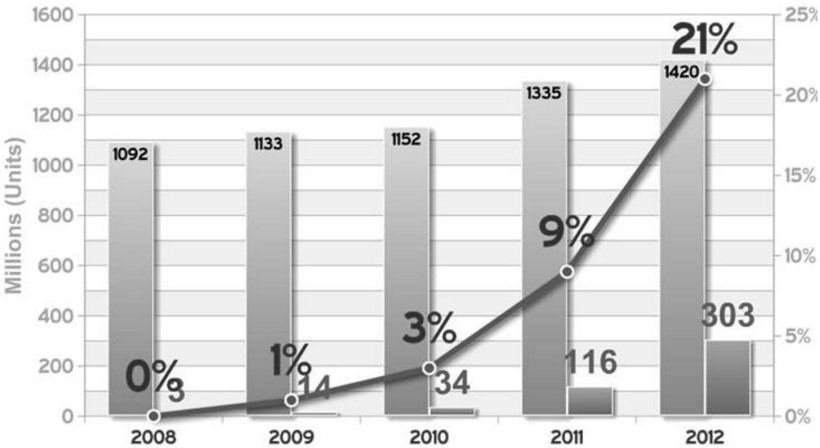

Fig. 10.3 Shipment of NFC enabled mobile phones [2]

Another possibility for the use of NFC technology is in the field of interconnection of different wireless devices. This interconnection in fact provides much higher data rates but usually requires tedious parameterization, password input etc. NFC allows bypassing these procedures by simple approximation of two separate devices.

For transmitting small amount of data, NFC communication rate (424kbps) is sufficient enough. In case of higher data volume transmission, NFC is able to establish, for instance WiFi or Bluetooth communication within a second, without the need of any parameterization of both devices. Connection to Wi-Fi home network can be done by a simple touch of router with the user's smartphone.

Fig. 10.4. Establishing NFC connection by device aproximation

NFC technology uses unregulated global zone of 13,56MHz. Data rate at the beginning of communication depends on the particular devices and their mutual distance is 103, 212 or 424kbit/s, but data rate may be adapted after connection establishment. Signal range due to electromagnetic induction transmission principle is not greater than 20cm but in fact, for these types of applications it is adequate.

10.4. NFC Access control systems

The potential of NFC use in the sphere of automation can be found in more ways. First one lies in building access control. NFC will probably improve current access control systems based on RFID plastic cards credentials for another options. Traditionally, an employee presents a plastic smartcard loaded with his/her access control authorization that transmits to a reader attached to a door itself. Once transmitted, the employee data travels from the reader to a centralized database usually over Ethernet to determine if the data is admissible. If granted, the data travels back via the costly installed wiring to the door lock, which open for an authorized employee.

Fig. 10.5. NFC based access control system

NFC based access control systems do not require the employee to carry a smart card, credentials are embedded on a NFC chip within the smartphone. Once at the door, user's smartphone reads the NFC door chip and sends out a signal over mobile internet which communicates directly with the server that stores the access control database. After the employee is granted or denied the authorization to enter the door, the centralized database sends digital key directly back to the mobile device over wireless internet. The whole process takes a second and its main benefit is eliminating the need for wiring between the database and the door.

So the most fundamental benefit of implementing NFC technology into smartphones is not only changing mobile device into a digital key, but also the possibility of delivering keys digitally, which has never been possible before.

10.5. Rating plates

Another field for NFC technology use in industry may be found in electronic rate plates. Precise identification of components such as motors, sensors, invertors or power modules in maintenance process is not always simple. There are lots of situations, when common rate plates are faded, soiled corrupted, or even there are no rate plates at all.

These components are often part of compact device or production line where it is difficult or even impossible to read the rate plate without intricate disassembling. Even if the device rate plate provides basic information, obtaining further details requires searching and downloading of producer catalogues and extensive datasheets.

All these difficulties could be eliminated by implementing embedded NFC tags into device cover, These tags, passive circuits as well as RFID chips are able to provide basic information necessary to device identification. All the important component data may be red by simple approximation of smartphone to the module. URL to particular datasheet, ensuring immediate download, could be part of this information.

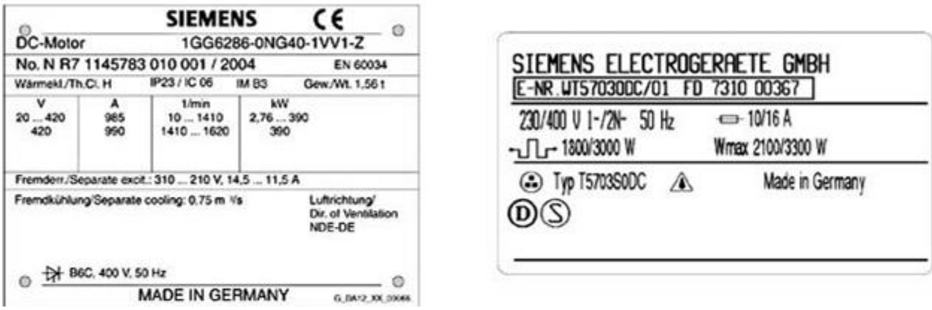

Fig. 10.6. Typical rating plates

In case of „intelligent" devices such actuators or active sensors, able to evaluate dynamic values itself, options mentioned above may be upgraded by transmitting dynamic values by means of active NFC module. Reading actual speed of actuator or distance measured by sensor or other important values could be done by simple approximation of reading device, without connecting to the main data bus. This option could be very convenient not only for maintenance purposes but also for developing process.

It is a matter of implementation whether this kind of communication would allow some software changes or even device control, such as jogging, speed set point input or basic parameterization.

Conclusion

Smartphones and other mobile devices will most probably take over the role of identification cards, today's credit cards and maybe they will also replace classic keys as well. The fact that NFC technology is developing rapidly, is proved not only by its hardware coverage expansion. NFC congresses and conferences are held all over the world, showing last inventions and designers ideas. Recent experience has shown, that implementation of this technology into particular devices, readers or tags is crucial for enforcing in practice, whilst on the other hand merging functions of several identification items into one electronic device, connected permanently to the Internet raises high safety demands on developers.

It is difficult to exactly predict next development of NFC as well as its impact to other current technologies so far. However it is important to have basic knowledge about this progressive technology, its possibilities, recent trends and other potentials of use.

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References

[1] Zjednotí NFC všetky bezdrôtové technológie? http://www.sos.sk/?str=1260
[2] NFC eLearning: http://www.ascendia.ro/work/eLearning/mobile_nfc/#menu
[3] Piotrowski A., Nieszporek T.: Setting up a work centre based on the Profibus network, Robotics in Theory and Practice, ROBTEP 2012

NFC TECHNOLOGY AND AUTOMATION APPLICATIONS

Abstract:
The article describes possibilities and options of new wireless technology – Near Field Communication. Brief history of NFC and short overview of current wireless technologies is presented in the beginning. Wireless payments and other interesting NFC possibilities including access control systems, rating plates or intelligent device implementation in automation applications are discussed in detail.

Keywords: NFC, wireless, access control, RFID, rating plates