Optimal Scheduling for Dependent Details Processing Using MS Excel Solver

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Abstract: *Scheduling is a key factor for manufacturing productivity. Efficient scheduling can improve on-time delivery, reduce inventory, cut lead times and improve the utilization of bottleneck resources. Because of the combinatorial nature of the scheduling problems, it is necessary to use proper optimization tasks. The paper presents an approach for defining the optimal processing scheduling, minimizing the total processing completion time on a limited number of machines with sequence-dependent processing of a number of discrete details. The optimization scheduling problem corresponding to the technological restrictions and requirements is formulated and solved by means of the Solver in MS Excel system. The proper methodology is proposed on the basis of a practical example and is tested and implemented in the practice of a metalworking CNC machines producing company.*

Keywords: *dependent details processing, optimal manufacture scheduling, MS Excel Solver model.*

1. Introduction

Planning and scheduling are important tools for manufacturing and engineering and can have a major impact on the productivity of the processes. In manufacturing the purpose of scheduling is to minimize the production time and costs, by defining what to make, when, with which staff, and on which equipment. Production planning and scheduling aims to maximize the efficiency of the operations and to reduce costs [1, 2, 3]. Backward and forward scheduling can be used to allocate plant and machinery resources, to plan human resources and production processes

and purchasing of materials. Forward scheduling plans the tasks when the date resources become available to determine the shipping date or the due date. Backward scheduling plans the tasks from the due date or required-by date to determine the start date and/or any changes in the capacity required.

In the literature there are various studies that focus on the efficient scheduling implementing approaches [4, 5, 6, 7]. Lee and Liman [8] consider the scheduling problem of minimizing total completion time with two parallel machines where one of the machines is always available and the other one is available from time zero up to a fixed point in time. By enumeration one can optimally solve problems with a finite set of feasible solutions to obtain better solutions [9].

The production process includes all activity as details processing time, available machines, technological restrictions, etc. This information will be used to determine the start and the end time moments for each operation, the sequence of the operations, the details route, i.e. a production scheduling corresponding to all requirements. It is always desirable the production scheduling to be the best, i.e. optimal according to some criteria.

The paper is based on a real scheduling problem from the practice of a CNC metalworking machines production company in defining the optimal processing schedules. The goal is to minimize the total processing completion time considering the technological restrictions, operations processing time and the available machinery recourses. It is well known that scheduling problems are sensitive to processing time data and the system resources can be utilized much more efficiently by appropriately planning of the details processing [12].

As a result of the progress in computer technologies and scientific investigations in the operational research area, the efficient mathematical approaches [10, 11] can be used for optimal production scheduling. MS Excel Solver was chosen as a tool for the optimization problems solving. The Microsoft Excel Solver combines the functions of a graphical user interface (GUI), an algebraic modeling language and optimizers with implemented different algorithms for linear, nonlinear, and integer problems solving by means of algebraic formulas. Excel's formula language can express a wide range of mathematical relationships and provides both interactive and user-programmable ways to define the mathematical programming problems [13].

2. Problem definition

The considered problem is taken from the practice of a CNC metalworking machines manufacturing company. There are a number of different details and each one has to comply with different technological restrictions. For each individual detail there are multiple operations to be performed on different machines. Each operation corresponds to a predefined processing time. It is evident that only one detail can be processed at a time on one and the same machine. The optimal scheduling should give the distribution of the operation times − operation start and end time moments of details among the machines reducing the mechanical detail processing time and the machines idle time. The available machines are of limited

number and they are not mutually substitutable. All details have to be processed and available at the preliminary fixed time moment for the assembly.

Let us assume that there are 5 details (D1, D2, D3, D4 and D5) needing different technological operations (O1, O2, …, O8) with specific processing times duration on 4 processing machines (M1, M2, M3 and M4). There exist also predefined technological orders of the details processing. All of the information data needed is shown in Table 1.

Table 1. Processing details technological data

No	Detail	Technological Operation	Processing Time, hours	Machine Type
1	D1	O1	8	M1
		O2	6	M2
		O3	6	M4
2	D2	O1	8	M1
		O4	8	M3
		O2	8	M2
		O3	4	M4
3	D3	O5	4	M1
		O6	1	M2
		O7	2	M3
4	D4	O5	6	M1
		O7	8	M3
5	D5	O4	6	M3
		O8	8	M4
Note: The detail D5 could be processed at any time (not necessarily last) provided that the machines M3, M4 are not occupied.				

The main problems related to the details processing are as follows:

• The details moulding is done in some outside companies and the delivery time moment should be defined. The earlier deliveries take up the storehouse and are not cost efficient. The late deliveries influence the assembling process and affect the time delay costs.

• Only one detail can be processed on a single machine at a time. That machine will be available for the next detail processing after completing of the previous detail processing. Each of the details has also technologically defined machines order processing (see Table 1).

• There exists technological details assembly sequence influencing the details processing order (see Table 1).

The problems above described can be solved by details processing schedule taking into account the existing technological restrictions. It would be preferable if that processing schedule were the best one, i.e., the optimally defined by a proper mathematical model and relevant optimization task solution.

3. Optimization task formulation

There are multiple operations to be performed for each detail with different technological sequence, on different machines and with different operation

duration. There exist restrictions that only one operation can be performed on one and the same machine at a time. The problem is to optimize the total processing time duration for all details and to find the best start and the end time moments for each operation for all details.

Using the information shown in Table 1, the following decision variables are introduced:

• X_{1E}, X_{2E}, X_{3E}, X_{4E}, X_{5E} – the finish processing time moment for each detail (D1 to D5);

• X_{11}, X_{12}, X_{14} – the starting processing time moment for the detail D1 on machines M1, M2 and M4;

• X_{21}, X_{23}, X_{22}, X_{24} – the starting processing time moment for the detail D2 on machines M1, M2, M3 and M4;

• X_{31}, X_{32}, X_{33} – the starting processing time moment for the detail D3 on machines M1, M2 and M3;

• X_{41}, X_{43} – the starting processing time moment for the detail D4 on machines M1 and M3;

• X_{53}, X_{54} – the starting processing time moment for the detail D5 on machines M3 and M4.

The objective function could be to minimize the total time duration for all details processing:

(1) $$\min (X_{1E}+X_{2E}+X_{3E}+X_{4E}+X_{5E}).$$

The optimization task is subjected to the technological restrictions expressing the operational processing sequence for each detail:

(2) $$X_{12} - X_{11} \geq 8,$$
(3) $$X_{14} - X_{12} \geq 6,$$
(4) $$X_{1E} - X_{14} \geq 6,$$
(5) $$X_{23} - X_{21} \geq 8,$$
(6) $$X_{22} - X_{23} \geq 8,$$
(7) $$X_{24} - X_{22} \geq 8,$$
(8) $$X_{2E} - X_{24} \geq 4,$$
(9) $$X_{32} - X_{31} \geq 4,$$
(10) $$X_{33} - X_{32} \geq 1,$$
(11) $$X_{3E} - X_{33} \geq 2,$$
(12) $$X_{43} - X_{41} \geq 6,$$
(13) $$X_{4E} - X_{43} \geq 8,$$
(14) $$X_{54} - X_{53} \geq 6,$$
(15) $$X_{5E} - X_{54} \geq 8,$$

and the restrictions to perform only one operation on one and the same machine at a time:

(16) $$X_{21} - X_{11} \geq 8,$$
(17) $$X_{31} - X_{21} \geq 8,$$
(18) $$X_{41} - X_{31} \geq 4,$$

(19)	$X_{32} - X_{12} \geq 6,$
(20)	$X_{22} - X_{32} \geq 1,$
(21)	$X_{23} - X_{53} \geq 6,$
(22)	$X_{33} - X_{23} \geq 8,$
(23)	$X_{43} - X_{33} \geq 2,$
(24)	$X_{14} - X_{54} \geq 8,$
(25)	$X_{24} - X_{14} \geq 6.$

All decision variables are nonnegative, i.e.

$$X_{ij} \geq 0 \text{ for } i = 1, \ldots, 5 \text{ and } j = 1, \ldots, 4.$$

Constraints (2)-(15) express the needed technological operations processing sequence of each particular detail as follows:

- (2)-(15)   – for D1 on the machines M1, M2 and M4;
- (5)-(8)   – for D2 on the machines M1, M3, M2 and M4;
- (9)-(11)   – for D3 on machines M1, M2 and M3;
- (12)-(13)   – for D4 on machines M1 and M3;
- (14)-(15)   – for D5 on machines M3 and M4.

The constraints (16)-(25) indicate the restrictions for the availability of the machines and the needed technological operations processing order between all the details.

The total time duration of all the details processing T can be calculated as a difference between the end time of the last detail processed and the start time for the first processed detail:

(26) $T = \max (X_{iE}) - \min (X_{i1})$ for $i=1, \ldots, 5.$

4. Using MS Excel for optimal details processing scheduling

Microsoft Excel is available as a part of the popular MS Office package. It has an add-in module for optimization problems solving, the so called – Solver, that can be used for optimal tasks solving. As MS Office Excel is a widespread and used software system it has the advantage to be well known, thus making sense to use is as a tool for details processing scheduling. A proper methodology for details processing scheduling by Solver using is described bellow.

First of all some explanatory information can be entered in the spreadsheet table area:

1. Information about the problem, the used abbreviations legend, etc., in the cells A1:X7.

2. The cell E8 is chosen to store the overall process time duration and some explanatory information text about it is entered in cells A8:D8.

3. Other titles for the table sections are entered in the cells A9:A24 as "*Details machining sequence on different machines*" and in the cells B9:B10 – "*Detail processing*", C9:C10 – "*Machine*", D9:D10 – "*Time, h*".

Then the different table sections are filled in with appropriate information and data:

4. The processed details are referenced in cells B11:B13 – "D1", B14:B17 – "D2", B18:B20 – "D3", B21:B22 – "D4", B23:B24 – "D5".

5. In the cells C11:C24 the sequence of the machines operations for each detail is entered accordingly to Table 1.

6. The time duration for each detail processing on the different machines i.e., the right hand sides of the restrictions (2)-(15) are entered in cells D11:D24.

7. The cells F10:X10 are reserved for the decision variables x11, x12, x14, ..., x4E, x5E and the cells F9:X9 for their values. The corresponding titles "*Decision values*" and "*Variables*" are in the cell E9 and cell E10.

8. The restrictions (2)-(15) coefficients matrix is entered in the table area F11:X24. In the cells, that express the cross point of the restrictions rows and decision variables columns the corresponding to (2)-(15) coefficients ("+1" or "–1") are entered and the rest of the cells are filled with null values ("0").

At this stage the Excel worksheet should look as it is shown in Fig. 1.

Optimal sheduling for details processing

D1, D2, D3, D4, D5 - delails
M1, M2, M3, M4 - details processing machines

Maximum duration for all details processing in hours:

Detail processing	Machine	Time, hr	Variables	x11	x12	x14	x21	x23	x22	x24	x31	x32	x33	x41	x43	x53	x54	x1E	x2E	x3E	x4E	x5E
D1	M1	8		-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M2	6		0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M4	6		0	0	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
D2	M1	8		0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M3	8		0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	M2	8		0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0
	M4	4		0	0	0	0	0	0	-1	0	0	0	0	0	0	1	0	0	0	0	0
D3	M1	4		0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0
	M3	1		0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0
	M2	2		0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	1	0	0	0
D4	M1	6		0	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0
	M3	8		0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	1	0
D5	M1	6		0	0	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0
	M5	8		0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1

Fig. 1. Excel worksheet data

The information from the rest of the restrictions (16)-(25) is entered in the same way:

9. In cells A25:A34 – title "*Details processing sequence on the same machine*" and in the cells B25:B34 – details technological waiting order.

10. C25:C27 – waiting for machine M1, C28:C29 – waiting for machine M2, C30:C32 – waiting for machine M3, C33:C34 – waiting for machine M4.

11. The cells D25:D34 store the information about the right hand sides of the restrictions (16)-(25).

12. The restrictions (16)-(25) coefficients matrix is entered in the table area F25:X34.

The Excel Worksheet at this stage has to look as it is shown in Fig. 2.

Optimal sheduling for details processing

D1, D2, D3, D4, D5 - details
M1, M2, M3, M4 - details processing machines

Maximum duration for all details processing in hours:

	Detail processing	Machine	Time, hr	Decision values / Variables	x11	x12	x14	x21	x23	x22	x24	x31	x32	x33	x41	x43	x53	x54	x1E	x2E	x3E	x4E	x5E
Details machining sequence on different machines	D1	M1	8		-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		M2	6		0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		M4	6		0	0	-1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	D2	M1	8		0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		M3	8		0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		M2	8		0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0
		M4	4		0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	1	0	0	0
	D3	M1	4		0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0
		M3	1		0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0
		M2	2		0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	1	0	0
	D4	M1	6		0	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0
		M3	8		0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	1	0
	D5	M1	6		0	0	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0
		M5	8		0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1
Details processing sequence on the same machine	D2 waits D1	on M1	8		-1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	D3 waits D2		8		0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	D4 waits D3		4		0	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0
	D3 waits D1	on M2	6		0	-1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	D2 waits D3		1		0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0
	D2 waits D5	on M3	6		0	0	0	0	1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
	D3 waits D2		8		0	0	0	0	-1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	D4 waits D3		2		0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0
	D1 waits D5	on M4	8		0	0	1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0
	D2 waits D1		6		0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 2. Excel worksheet data

The information about objective function, its coefficients and overall processing time should be entered too.

13. A formula =SUMPRODUCT(F11:X11;$F$9:$X$9), is entered in cell E11, and is copied to cells E12:E34, so that it is adjusted to each particular cell address. For example, the cell E34 must have the formula: =SUMPRODUCT(F34:X34;$F$9:$X$9).

14. The objective function coefficients from (1) are entered in the row F36:X36.

15. The cell F37 is reserved for the objective function value, calculated by the formula =SUMPRODUCT(F36:X36;F9:X9)

16. Cells A36:E36 and A37:E37 are used for referencing information as "*Objective function coefficients*" and "*Objective function value*".

17. In cell E8 we enter the formula for calculating all details processing time duration i.e., the biggest value of the x_{iE} variables:

$$=MAX(F9:X9)$$

18. To let the Solver know which cells on the worksheet represent the decision variables, the constraints and the objective function, the "Tools"-"Solver" menu positions are chosen and in the "Solver Parameters" dialog window the corresponding information is entered:

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- $F$37 – for the objective function target cell,
- $F$9:$X$9 – for the variables,
- $E$11:$E$34>=$D$11:$D$34 and $F$9:$X$9>=0 – for the restrictions.

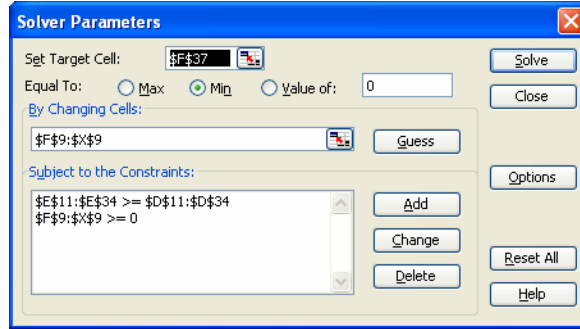The "Solver Parameters" dialog window should look as shown in Fig. 3.

Fig. 3. Solver parameters

To find the optimal solution, i.e. the optimal production schedule the "Solve" button is activated and the Solver returns the values for the objective function in the cell F37, the overall process time duration in the cell E8 and the variables values in the row F9:X9. The final spreadsheet screen is shown in Fig. 4.

Optimal sheduling for details processing

D1, D2, D3, D4, D5 - details
M1, M2, M3, M4 - details processing machines

Maximum duration for all details processing in hours: **36**

Detail processing	Machine	Time, hr	Decision values	0	8	14	8	16	24	32	16	23	24	20	26	0	6	20	36	26	34	14
			Variables	x11	x12	x14	x21	x23	x22	x24	x31	x32	x33	x41	x43	x53	x54	x1E	x2E	x3E	x4E	x5E
D1	M1	8	8	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M2	6	6	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M4	6	6	0	0	-1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
D2	M1	8	8	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M3	8	8	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	M2	8	8	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0
	M4	4	4	0	0	0	0	0	0	-1	0	0	0	0	0	0	1	0	0	0	0	0
D3	M1	4	7	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0
	M3	1	1	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0
	M2	2	2	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	1	0	0
D4	M1	6	6	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0
	M3	8	8	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	1	0
D5	M1	6	6	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0
	M5	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1
D2 waits D1	on M1	8	8	-1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D3 waits D2		8	8	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
D4 waits D3		4	4	0	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0
D3 waits D1	on M2	6	15	0	-1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
D2 waits D3		1	1	0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0
D2 waits D5	on M3	6	16	0	0	0	0	0	1	0	0	0	0	0	0	-1	0	0	0	0	0	0
D3 waits D2		8	8	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0
D4 waits D3		2	2	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0
D1 waits D5	on M4	8	8	0	0	1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0
D2 waits D1		6	18	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		Objective function coefficients:		0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
		Objective function value:	130																			

Fig. 4. The final spreadsheet with the optimization task solution values

The created in this way Excel spreadsheet model can be modified and extended to comply with different optimization models and formulations. For example, the operations processing time values can be modified in the column D11:D34, the other restrictions can be entered in table area F11:X34, etc.

The MS Excel Solver gets the solution of the formulated optimization problem within a second on a PC with CPU Intel Celeron 2.67 GHz, 1.24 GB RAM under MS Windows XP OS. The best overall process time is 36 hours (cell E8) and the details processing schedule can be constructed by the values of the decision variables. The corresponding graphical presentation the processing schedules for all details is shown in Fig. 5.
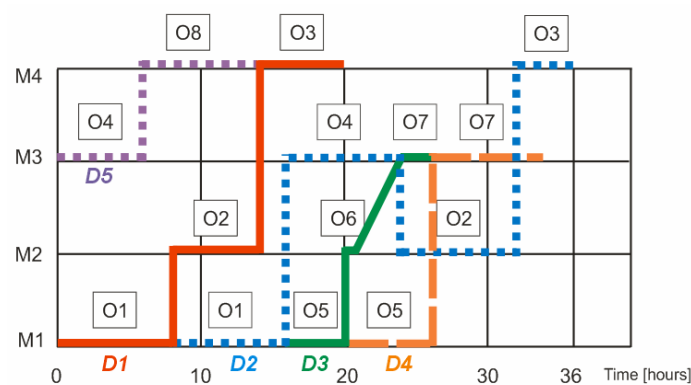
Fig. 5. Processing schedules for details D1, D2, D3, D4 and D5

For example, the detail D1 starts its processing on machine M1 at the time moment $X_{11}=0$ (cell F9), on machine M2 at time moment $X_{12}=8$ (cell G9) and on machine M4 at time moment $X_{14}=14$ (cell H9). The processing end-time moment for the detail D1 is $X_{1E}=20$ (cell T9). Because of the fact that the detail D5 has some freedom in the processing order its processing starts on machine M3 at the same moment as D1, i.e., $X_{53}=0$ (cell R9), on the M4 its processing continues at the time moment $X_{54}=6$ (cell S9) and finishes at the time moment $X_{5E}=14$ (cell X9). The other decision variables values from row F9: $X9$ can be used to get the corresponding start and end-time moments for others details processing.

5. Conclusion

The paper describes a typical scheduling problem of multiple details processing on a limited machines number considering some technological restrictions about details processing order, machines processing order for each detail, availability of the machines and operations time durations. The real life example from the practice of CNC metalworking machines manufacturing company is used to create an optimization details processing model and an optimization task. The solution of the optimization task gives the optimal distribution of the start and end-time moments for processing of each detail and the overall processing time duration, i.e. the optimal processing schedule. It can be used not only to organize the details

processing and to decrease the machines delays but also to forecast the time moments for details moldings supply time moments thus decreasing the storage needs.

The proper methodology for solving of the formulated optimization task by means of the MS Excel spreadsheet add-in module Solver is described. The approach described in the paper was tested and implemented in a CNC metalworking machines production company for defining the base details optimal processing schedules on a limited number of available machines. The proposed methodology uses the advantage of the popularity of the MS Excel system and can be easily applied, modified and extended to reflect different practical needs.

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