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SUITABLE PRODUCTION TOOLS SELECTION WITH THE USE OF EVOLUTIONARY ALGORITHMS

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Abstract. This paper deals with the use of a production equipment simulation in the design of production systems, more specifically the welding equipment in the automotive industry. Based on the simulation results, a matrix, which defines the possibility of using given manufacturing tools (in this case welding guns are considered) to connect the plates using the electrical resistance spot welding process, is created. This matrix generates a set of several numbers of solutions depending on other parameters, such as the lowest price, the lowest number of used welding guns, etc. The goal is to solve this task. The solution is presented using mathematical programming. Specifically, the method of genetic evolutionary algorithms is being used. The Solver software is used to optimize the selection of the welding guns' combination. The Solver is an add-on in MS Excel. The case study shows 15 welding points weldment on which the availability of 20 types of welding guns was simulated. The result is an ideal combination of 2 types of guns for the lowest price.

Keywords: Design process, production system, production process, simulation, body shop, automotive industry, evolutionary algorithms.

1. Introduction

Generally, the design and the optimization in the automotive industry equipment is driven forward by the constant search for an ideal solution. This can be generalized for any production industry. Equipment can be considered as ideal when it meets the following basic conditions:

- Lowest price
- Minimal production area
- Required capacity
- Reaching legal regulations and standards
- Flexibility
- Ergonomics

The system design and even overall design of production systems require a step-by-step modelling method, i.e. creation of opportunities and their technical, organizational and economic evaluation. For more complex tasks, it is necessary to use simulations to evaluate the dynamic ability to coordinate all the functions and elements of the production system over time, occupying space with qualitative and quantitative requirements. [1]

Production planning is a problem of multidimensional optimization where there is a number of partial issues, such as product selection, product allocation, manufacturing sequence, etc. that need to be solved at the same time. In the following text, an improved genetic algorithm is introduced to find an ideal solution. Experimental results have proved that the proposed genetic algorithm structure is better than a conventional structure. This is because the proposed genetic algorithm allows "learning" from its own experience. [2]

Running a simulation to support production planning can be used for an early issue detection [3]. Simulations are commonly used for a design valuation during the late stages of product development [4]. It also provides the ability for production capacities tests, simulation model experiments and various scenarios creations [3]. Hence, research suggests an early-stage systematic physical analysis in the product design. There are also examples using different simulations to prove a product manufacturability. However, there is a dearth of research that investigates the application of simulation tools that can support the assessment of preliminary production operations that utilizes a variety of production resources to produce the same emerging product variety [4].

Big data analysis has been successfully used in many areas, including product lifecycle management, supply chain management, and predictive maintenance. The aim is to design a machining optimization based on a big data analysis. Each production machine is represented by its attributes. Once the data are ready, the resources are optimized. This approach is validated by a simplified case study with implemented hybrid genetic algorithms. [5]

The main technology used in automotive bodywork production lines is electrical resistance spot welding. When designing this type of production line, it is necessary to solve the appropriate production tools,

BO VO	5QF.803.203
TUNNEL	5QF.803.296
SCHWELLER LI	5QF.801.251
SCHWELLER INNEN NWB	5QA.803.755
BLECHMUTTER 7/16-20UNF-2B-B	N.989.911.01
MONTAGET.SCHWELLER VORN	5QA.802.307
MONTAGET.SCHWELLER HINTEN	5QA.802.311
VERST.WAGENHEB.AUF	5QF.803.477
SCHOTTTEIL SCHWELLER	5QA.804.499
TRAEGERTEIL RADHAUS	5QF.813.119
SCHWELLER RE	5QF.801.252
BODEN,VORN 2630 MM	5Q0.803.205.B
BODEN,VORN 2630 MM	5Q0.803.206.B
AUFN SITZ LI	5QA.802.225
SITZBEF SCHWELL LI	5QA.802.569
SITZBEF TU LI	5Q0.802.381.B
SITZQUERTRAEGER LI	5QA.803.231
SITZQUERTRAEGER	5Q0.803.233.B
VERSTAERKUNG SITZQUERRTAEGER	5QA.803.285
AUFN SITZ RE	5QA.802.226
VERSTEIFUNG	5QF.803.579
VERSTEIFUNG	5QF.803.580

Figure 1. Part list.

in this case, it is a selection of the most suitable welding guns that can weld the prescribed welding points in the required quality.

Nowadays, computer simulation methods, combined with the experience of the product designer are used to select the best design of welding guns. In order to run the simulation with production tools, it is necessary to prepare a simulation model at first. For designing welding lines, the Czech car manufacturer ŠKODA AUTO a.s. uses planning software called Process Designer by Siemens. This software is the first used to prepare a product, in a specified case, it is part of the whole bodywork.

2. Simulation

Every assembly is defined by its part list, every pressed metal sheet has a 3D model with an exact location (x, y, z) in the space. The part list is a list of all input parts (pressed metal sheets, weldments) with the part name and number. The specific level is assigned to every part and defines the time when the part enters the bodywork (welding). The part list also has more attributes describing the product (material, surface finish, sheet thickness, production depth, start and finish date of usage of the bodywork). The 3D weldments model is created using the CAD system, in this case, the Catia software is used, see Figures 1 and 2.

Welding elements are specific joint types, such as electric resistance spot welds, fusion welds, adhesives, bolts, etc. The elements are designed in the CAD system as well. They contain the following attributes: weld name, weld type, position in space (x, y, z), a combination of joined parts (2 sheets welds, 3 sheet welds) and clear assignments to pressed metal sheets that need to be welded.

In order to simulate the welded part's manufacturability, production tools library has to be created for the DF (Digital Factory) system. In this case, it is library of standard welding guns, such as in Figure 3.

Now all the necessary resources are reached to make the first production tool selection, the suitable welding guns need to be selected. The selection method is called a welding-guns availability simulation. This simulation method checks selected welding guns with the requested weld points. The method is about placing a 3D model of welding guns on each welding point. The guns than rotate around the point in 10°steps. Next step is the rotation of welding guns around their axis by 180°and the process is repeated. The simulation tool evaluates whether there is at least one position of the welding guns relative to the weld point, where there is no collision between the guns and the assembly.

The result of the simulation process checking the availability of welding guns is a matrix. This matrix holds for the set of welding points and welding guns' information about collision-free welding possibility. In Figure 4 is an example of such a simulation where the "+" sign indicates a collision-free situation of the guns and the welding point and the "-" sign indicates a collision.

3. Ideal solution

Using the simulation, welding guns, which can be used to weld to a specific welding point were identified. The best result is when one type of welding guns can weld all selected points. A case may also occur, where the weld point is not weldable by any guns

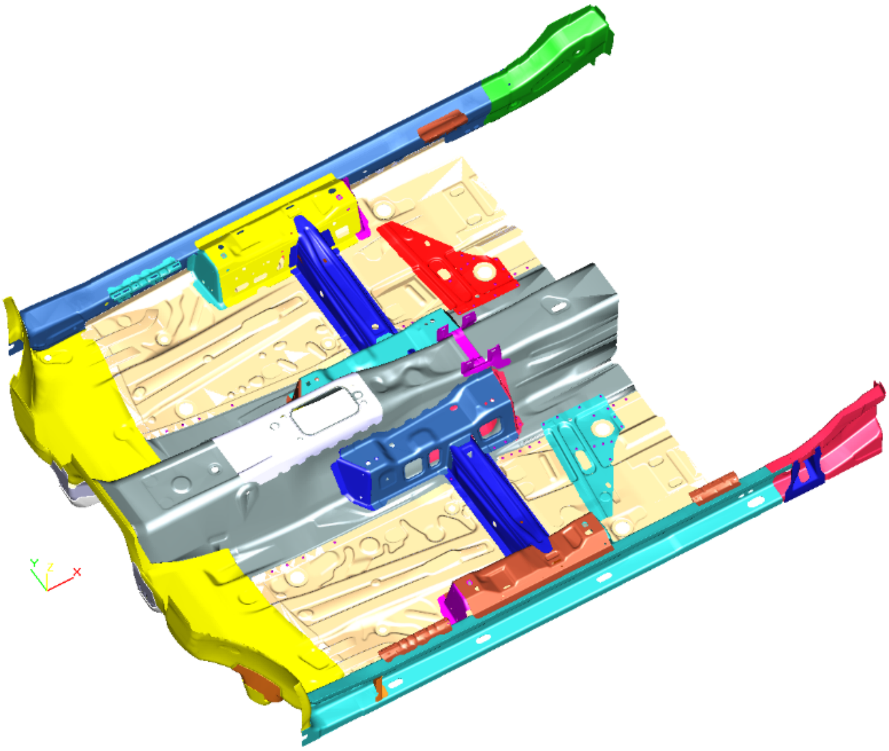

Figure 2. Assembly (Product).

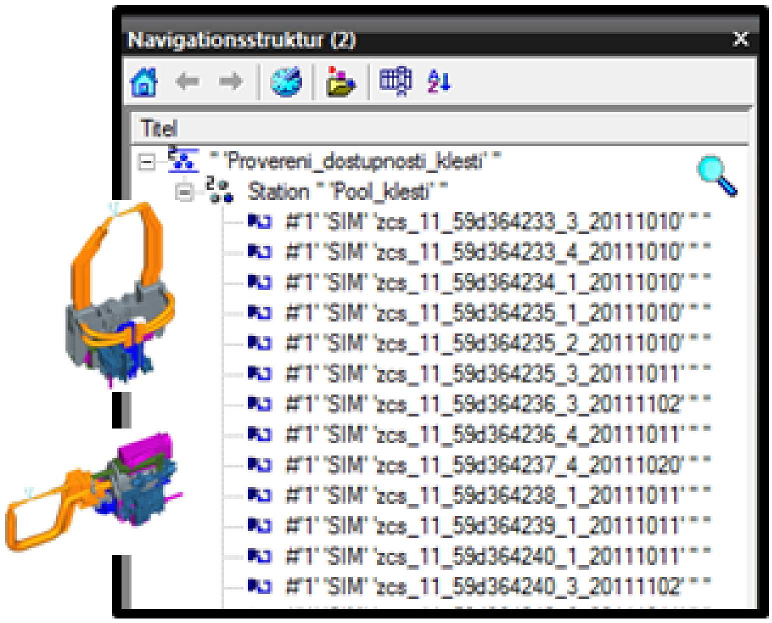

Figure 3. Welding guns library.

Zangen	Alle	cps0001	cps0003	cps0005	cps0006	cps0007	cps0008	5cps0009	cps0010	dps0001	dps0002
C 64233	-	+	+	+	+	-	-	-	-	-	+
C 64234	-	-	+	-	-	-	-	-	-	-	-
C 64235	-	+	+	-	+	+	-	-	-	-	+
C 64236	-	+	+	-	-	-	-	-	-	+	-
X 63979	-	+	+	-	+	+	-	+	+	-	+
X 63965	-	-	-	-	+	+	+	+	+	-	+

Figure 4. Simulation result.

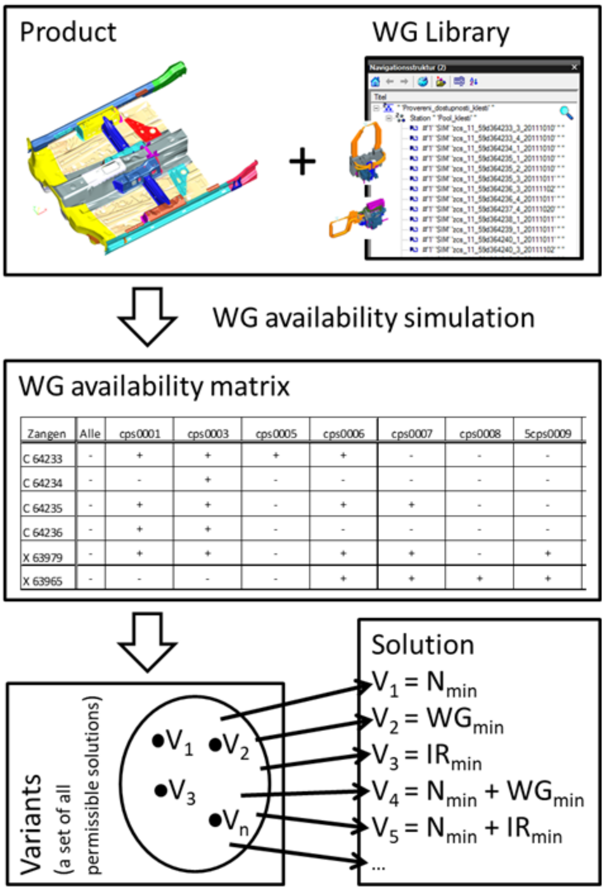

Figure 5. Optimization task.

saved in the library. In this case, the construction of special welding guns is necessary, so the unique point can be welded. Usually, the simulation confirms the weldability of all the points by a combination of several guns. The set n solution is obtained where there are n combinations of guns that can weld the selected set of points.

The goal is to choose the ideal solution from this n solution set, as shown in Figure 5. The selection can be, for example, based on the lowest price. The unit price for every welding gun can be added to the solution matrix, so it can look for a combination where the price will be lowest.

Mathematical programming can be used to solve such a task. The task of mathematical analysis is to find extremes (maximum, minimum) of the multiple variables function with boundary conditions.

If the function, for which an extreme is solved for, is linear and the boundary conditions are linear as well, the whole task is treated as a linear programming (LP) problem. [6]

The task of the LP is to find the extreme of a linear function in which the variables are bound by a set of linear limiting conditions: [6]

$$m < n; \quad b_i \geq 0$$

$$\sum_{j=1}^{n} a_{ij} x_{ij} \leq b_i$$

$$\text{for } i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n;\ x_j \geq 0$$

$$F = \sum_{j=1}^{n} c_j x_j = min$$

The basic variables are defined in Table 1.

The goal is to find a configuration $\vec{K}$, minimizing the total price T over the condition of overall success (that is for $V^{\vec{K}} = N_W$, it means that the selected configuration can meet all the goals).

Since this is a multidimensional task with discrete parameters, one of the variants of the global evolutionary optimization is chosen.

4. Evolutionary algorithms

Evolutionary algorithms are global optimization algorithms, they can approximately solve tasks that are not possible to solve exactly using current computing power, are extremely time-consuming, or require human intuition. These algorithms use the principles known from evolutionary biology, especially Darwin's survival of the fittest principle.

To make sure the evolution will work, three things are necessary:

(1.) Two existing solutions can form new "averaged" solution, this is called crossing.

(2.) The created solution can be randomly manipulated, this is called mutation.

(3.) For any individual, another suitable individual is selected, this is called natural selection.

This principle often finds high-quality problem solutions - without the need of inventing a specialized algorithm to solve a particular problem. The only thing the algorithm needs to know is which solutions are stronger and which are weaker. This is a simple task carried out by a human, however, creating a good solution can be unbelievably difficult. [7]

Different tasks make it possible to represent the solution in different ways. The solution is represented by a chromosome that can be specified as:

- Binary numbers vector (zeros and ones sequence)
- Real numbers vector
- Charts on others

The entire vector that represents the solution is called the chromosome. The chromosome consists of genes that can have different values. The specific value of one gene is called an allele. See Figure 7.

The size of the genotype may vary. In this case, both the mutations and crossing should have been precisely designed to work with different sizes of chromosomes. [4]

N_T	Number of tools (for example welding guns)
N_W	Number of tasks (for example welding points)
$H = \{0,1\}^{(N_T \times N_W)}$	Solution matrix
$H_{ij} = 0$	With the i-tool, it is not possible to reach j-task
$H_{ij} = 1$	With the i-tool, it is possible to reach j-task
$\overrightarrow{P} \in \mathbb{R}^{N_T}$	Price vector
P_i	Price of the i-tool
$\overrightarrow{K} \in \mathbb{N}_0^{N_T}$	Configuration vector
K_i	Planned amount of i-tool
$T = \sum_{j=1}^{N_T} K_j P_j$	Total price
$\overrightarrow{U^{\overrightarrow{K}}} \in \{0,1\}^{N_W}$	Success vector for the configuration $\overrightarrow{K}$
$U_i^{\overrightarrow{K}} = 0$	i-task is not possible in configuration $\overrightarrow{K}$ (i.e. $\forall j: \ H_{ji} = 0° \vee K_j = 0$)
$U_i^{\overrightarrow{K}} = 1$	i-task is possible in configuration $\overrightarrow{K}$ (i.e. $\exists j: \ H_{ji} = 1° \wedge K_j > 0$)
$V^{\overrightarrow{K}} = \sum_{j=1}^{N_W} U_j^{\overrightarrow{K}}$	Overall success of configuration $\overrightarrow{K}$

Table 1. Basic variables.

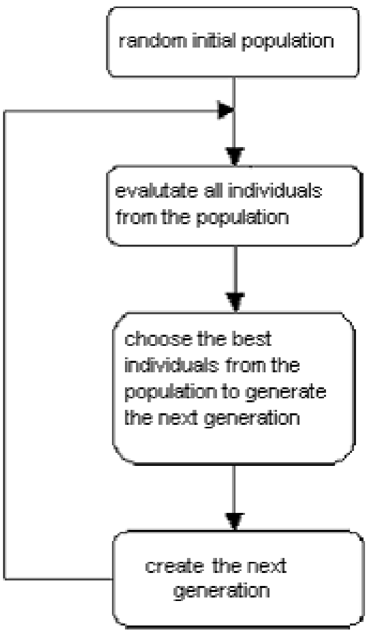

Figure 6. General EA process.

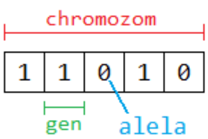

Figure 7. Bit string.

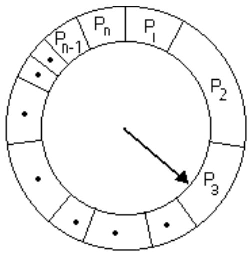

Figure 8. Roulette wheel.

Crossing

One of the most common ways of crossing is a simple crossover method. It is usually done with one or two points that are randomly selected in the chromosome and the genes are exchanged between those two. [7]

Mutation

For the mutation, it should apply that bigger changes occur with fewer probabilities than small changes. The mutation method depends on the representation method. If a binary chromosome is present, the mutation can be done by random bit exchange. In the case of the real number chromosome, random values (given e.g. by the normal distribution) can be added to gene values. If the solution by a chart is presented, the mutation can be adding a node, an edge, changing the order, etc. [8]

Selection

The commonly used genetic-algorithm selection method is the roulette wheel selection. Imagine a roulette wheel divided into different size fields. The size of each piece corresponds to the individual's fitness value (see Figure 8). When the roulette spins, there is a higher chance that larger piece will be selected. Individuals with a higher fitness rating have a higher chance of being selected for crossing and to pass on their genes. [7]

	WP1	WP2	WP3	WP4	WP5	WP12	WP13	WP14	WP15	Costs	Quantity	Result
G1	0	1	1	1	0	0	1	1	1	100	0	0
G2	1	0	0	1	1	1	1	0	0	140	0	0
G3	0	0	1	1	0	1	1	1	1	130	0	0
G4	0	0	0	0	0	0	0	0	1	90	0	0
G5	1	1	1	0	1	0	0	0	0	110	0	0
G6	1	0	0	0	1	1	0	1	1	100	0	0
G7	0	0	0	0	0	1	0	0	0	150	0	0
G8	1	1	0	0	0	0	1	0	1	135	0	0
G9	1	0	1	0	0	1	0	0	0	140	0	0
G10	0	0	1	0	0	1	0	0	1	150	0	0
G11	1	1	1	1	0	1	0	0	0	150	0	0
G12	1	1	1	1	1	0	0	0	1	150	0	0
G13	0	1	0	0	0	1	1	1	0	130	0	0
G14	1	1	1	0	1	0	1	0	1	150	0	0
G15	1	1	0	0	0	0	1	1	1	150	0	0
G16	0	1	0	0	0	0	0	1	0	140	0	0
G17	0	0	0	0	0	0	0	1	0	130	0	0
G18	0	0	0	0	1	0	0	0	1	150	0	0
G19	0	0	1	0	1	1	0	1	1	140	0	0
G20	1	1	0	1	0	1	1	0	0	150	0	0
												0
Checksum	0	0	0	0	0	0	0	0	0	0		

FIGURE 9. Start matrix.

G1 – G20	Welding Gun
WP1 – WP15	Welding Point
Costs	Costs of Welding Gun
Quantity	Number of welding guns required for the best solution
Result	Quantity vs. Costs
Checksum	The check sum, number 1 is necessary for the correct result

TABLE 2. Description of the matrix..

5. Ideal Solution

The problem described above will be solved using the genetic evolution algorithm. The Solver optimization software will be used, this is the MS Excel add-on.

First, the matrix of the result is converted (composed of welding guns' availability) into the binary code and other parameters are added.

Individual variables are described in Table 2.

Now in MS Excel, under the "Data" tab, the "Solver" add-on is used and the basic parameters are set (see Figure 10).

Since the task is relatively complex and many variants need to be checked, it is recommended to change the basic optimization time setting to 3 minutes (see Figure 11).

The optimization itself is started with the "Solve" command, see Figure 12.

After the calculation is complete, the ideal solution is confirmed to keep (see Figure 13).

The ideal solution is the use of only two welding gun types - G3 and G5. The total cost of this combination is 240. It is still necessary to check the Checksum indicator, all values need to equal to 1 and the total sum should match the number of welding points, in this case, the total sum is 15.

In the considered case, for 20 welding gun types, where each type is capable to weld at least one welding point, more than 1.4 million combinations can be found. With Solver, the ideal combination was found after trying 119,500 combinations, which is about 8 % of all possible combinations.

6. Conclusion

The main feature of the production system simulation is to create multiple possibilities. The described partial simulation of the welding guns' availability solves the designing issue of the selection of welding guns. The result shows guns that are able to weld the selected point with the electric resistance welding method without a collision, but choosing the right combination of these guns is not resolved. Therefore, further analysis is required, with new variables such as price being added. This process gives many additional result combinations. The global evolutionary analysis

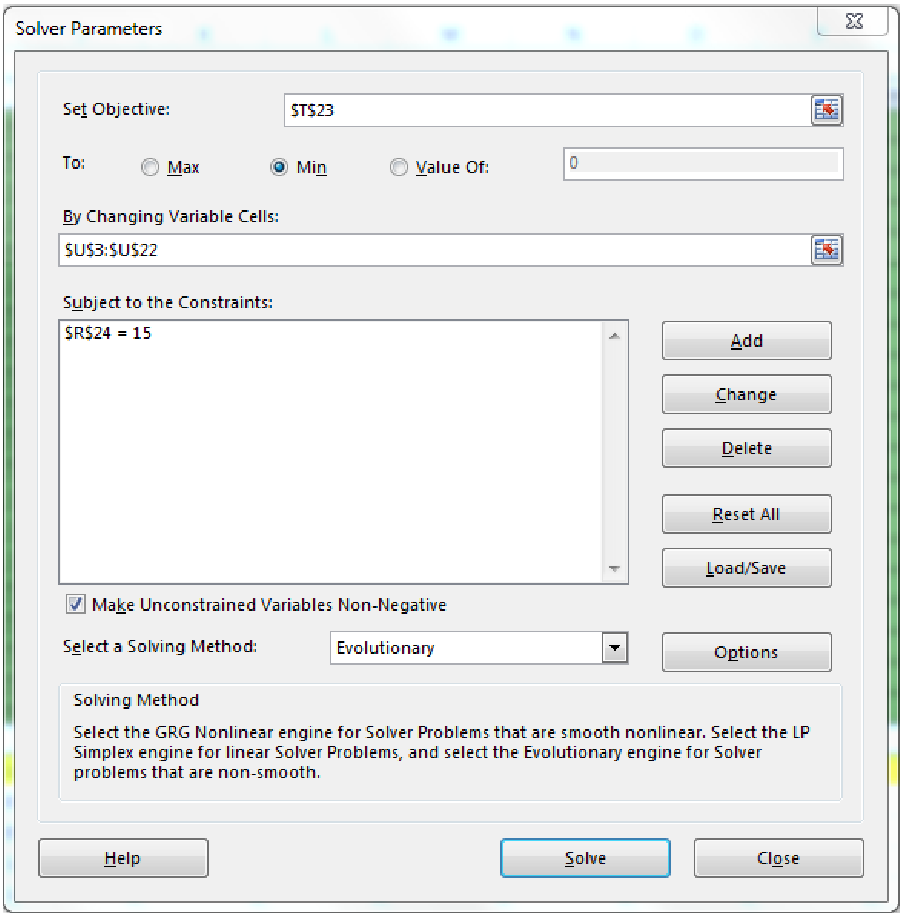

Figure 10. Solver parameters.

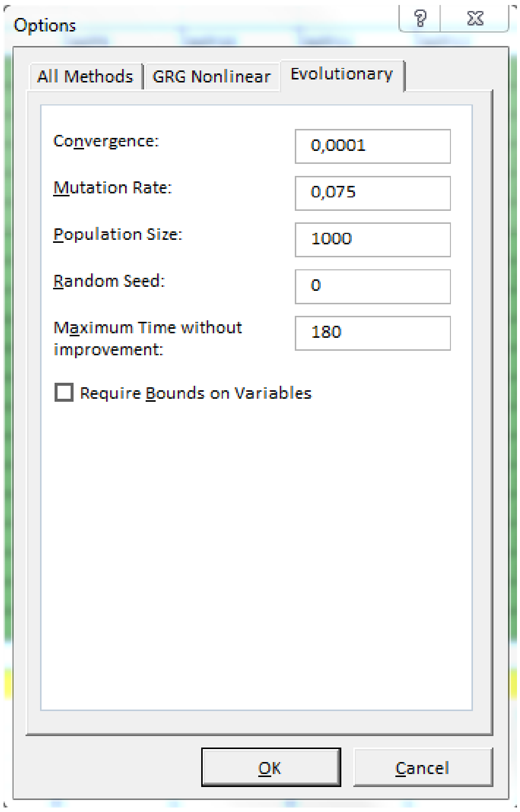

Figure 11. Solver options.

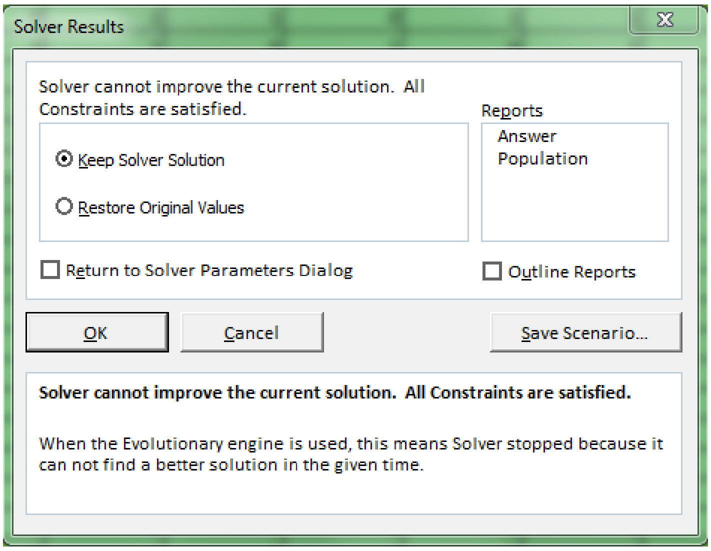

Figure 12. Solver results.

	WP1	WP2	WP3	WP4	WP5	WP12	WP13	WP14	WP15	Costs	Quantity	Result
G1	0	1	1	1	0	0	1	1	1	100	0	0
G2	1	0	0	1	1	1	1	0	0	140	0	0
G3	0	0	1	1	0	1	1	1	1	130	1	130
G4	0	0	0	0	0	0	0	0	1	90	0	0
G5	1	1	1	0	1	0	0	0	0	110	1	110
G6	1	0	0	0	1	1	0	1	1	100	0	0
G7	0	0	0	0	0	1	0	0	0	150	0	0
G8	1	1	0	0	0	0	1	0	1	135	0	0
G9	1	0	1	0	0	1	0	0	0	140	0	0
G10	0	0	1	0	0	1	0	0	1	150	0	0
G11	1	1	1	1	0	1	0	0	0	150	0	0
G12	1	1	1	1	1	0	0	0	1	150	0	0
G13	0	1	0	0	0	1	1	1	0	130	0	0
G14	1	1	1	0	1	0	1	0	1	150	0	0
G15	1	1	0	0	0	0	1	1	1	150	0	0
G16	0	1	0	0	0	0	0	1	0	140	0	0
G17	0	0	0	0	0	0	0	1	0	130	0	0
G18	0	0	0	0	1	0	0	0	1	150	0	0
G19	0	0	1	0	1	1	0	1	1	140	0	0
G20	1	1	0	1	0	1	1	0	0	150	0	0
												240
Checksum	1	1	1	1	1	1	1	1	1	15		

Figure 13. Result matrix.

is used to find the ideal solution out of the additional combinations including new variables. The MS Excel add-on called Solver was used for this analysis. This software allows you to check about 10,000 possibilities in a short amount of time and come out with the ideal one.

As an example, the availability matrix is presented with the combination of 15 welding points and 20 types of welding guns. To find the ideal combination of welding guns using the genetic evolution algorithm in MS Excel add-on Solver, about 8 % of all combinations were necessary to verify.

In today's bodywork, the weldments can reach up to 400 welding points. The standardized production is an attempt to have only certain types of welding guns. For the case of 50 welding gun types and 400 welding points, lowering the necessary combinations to find the ideal value below 10 % is very beneficial.

References

[1] A. Zelenka. *Projektování výrobních procesů a systémů*. CTU Publishing House, Prague, 1st edn., 2007.

[2] S. D. Dao, K. Abhary, R. Marian. An improved genetic algorithm for multidimensional optimization of precedence-constrained production planning and scheduling. *Journal of Industrial Engineering International* **13**(2):143 – 159, 2017. doi:10.1007/s40092-016-0181-7.

[3] Š. Václav, P. Košťál, Š. Lecký, et al. Assembly system planning in automotive industry with use of discrete event simulation. *Lecture Notes in Mechanical Engineering* pp. 503–515, 2018. doi:10.1007/978-3-319-75677-6_44.

[4] X. Gong, J. Landahl, H. Johannesson, R. Jiao. Simulation-driven manufacturing planning for product-production variety coordination. In *2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, pp. 2039–2043. 2017. doi:10.1109/IEEM.2017.8290250.

[5] W. Ji, S. Yin, L. Wang. A big data analytics based machining optimisation approach. *Journal of Intelligent Manufacturing* **30**(3):1483–1495, 2019. doi:10.1007/s10845-018-1440-9.

[6] J. Kožíšek, B. Stieberová. *Statistická a rozhodovací analýza*. CTU Publishing House, Prague, 2014.

[7] F. Streichert. Introduction to evolutionary algorithms. `http://www.ra.cs.uni-tuebingen.de/mitarb/streiche/publications/Introduction_to_Evolutionary_Algorithms.pdf`, 1991. University of Tuebingen.

[8] Y. Xinjie. *Introduction to evolutionary algorithms*. Springer, London, 2010. doi:10.1007/978-1-84996-129-5.