# BALANCING OF A MANUFACTURING WORKSTATION, USING A SIMULATION AND OPTIMIZATION MODEL

### Chaves Almanza F.D.<sup>(a)</sup>, Wellens A.<sup>(b)</sup>

<sup>(a),(b)</sup>Facultad de Ingeniería, UNAM-MÉXICO

<sup>(a)</sup>fabiodaniel@comunidad.unam.mx, <sup>(b)</sup>wann@unam.mx

### ABSTRACT

This paper describes the balancing of a manufacturing workstation in a metalworking industry, using simulation to predict the productivity of a workstation consisting of ten pressure welding machines, and afterwards optimizing the operation time, by assigning welding tasks to the different machines depending on the demand requirements. The operation time depends on the number of welding points that are achieved at the time, thus machine productivity is mainly related to the configuration required for each new product. Production and engineering teams of the facility are interested in knowing what would be the best workstation performance for future projects, considering possible machine settings. A simulation model was developed to get estimates of future machine productivity, obtaining the required parameters to optimize the workstation's overall operation time by means of an optimized task schedule.

Keywords: machine productivity, optimization, assignment problem, simulation

### 1. INTRODUCTION

Welding is the joining of metals applying heat and/or pressure, with or without the addition of an appropriate metal. Specifically, pressure welding implies the application of both heat and pressure, resulting in a macrodeformation of the base material to produce coalescence. For a detailed review of pressure welding see Jeffus (2011). This process is applied by the metalworking facility where this study took place, for manufacturing metal parts for the automotive industry, specifically for chair components. The facility deals with major automotive clients who often have high levels of costumer demands. To fulfill these requirements the factory has a workstation consisting of ten pressure welding machines, similar between them but coming from different manufacturers and with varying size and/or possible machine settings.

As car design changes constantly, car components have to be adjusted accordingly by design and engineering specialists of the automotive companies. These new parts are to be manufactured by the metalworking factory, and for each part the pressure welding machines need to be configured differently. This includes the design and creation of a specific guiding tool or production mold for each new part; its specification and cost has to be included in the project description.

The ten welding machines have slightly different specifications, and not all new automotive parts can be manufactured indistinctly in each of the machines, basically because of machine size constraints. Depending on client requirements and part size, generally two or three different machine configurations can be considered. For example, to join two screws to a foil part it is possible to operate the machine once (fixing both screws at the same time) or two times (fixing the screws one by one in two independent operations), depending on the size and position of the foil part and the location of the machine's adjusting tools to fix the foil. Of course, doing the operation in two independent steps will include each of them part handling, and overall operation time will increase and productivity will decrease consequently.

In order to provide decision criteria that can be used by the metalworking facility, the present study proposes the best workload assignment for the ten pressure welding machines, obtaining thus the optimal operation time. To achieve this, machine productivity was simulated in PROMODEL® for different setup scenarios, using as a basis historical production data (3 months) for similar parts. Afterwards, a linear programming model was applied to optimize production task assignment in order to obtain the smallest overall operation time and thus generate savings for the metalworking facility.

### 2. CONCEPTUAL APPROACH

The present research was based on the approach of Law (2015) to develop a simulation study. This approach involves a complete methodology that includes not only the construction of a simulation model, but also other important stages to develop a complete study. The set of stages defined by Law is: i) formulate the problem, ii) collect information and data and build a conceptual model, iii) validate the conceptual model, iv) program the model, v) validate the programmed model, vi) decide, make and analyse experiments, and vii) document and summarize the simulation results. Law is one of the most recognized authors in the field of simulation and his methodology is known to be consistent and effective in simulation studies all over the academic ambit.

In the present study, simulation results are used to construct a linear programming model that optimizes overall operation time. Because of the conditions of the problem studied, the linear programming model is based on the classical assignment problem. This problem is one of the fundamental examples of combinatorial problems in operations research, and it consists of finding a minimum weight perfect matching in a weighted bipartite graph (Brualdi, 2006).

In this study the instance of the problem considers ten metallic parts to be spot welded in ten pressure welding machines, working in parallel and without sequential operations. One of the parts involves a demand of 316,000 units, whereas other four parts each have demands of 32,000 units. The remaining five parts require manufacturing 79,000 units each, completing a total production of 839,000 units for the ten parts; it takes about 14 months to be completed in non-optimal conditions. The complete production of each part must be assigned to only one machine, depending basically on sizing and shape constrains and considering a specific required machine configuration for each part.

Many variations of the original problem have been studied. The most recognized should be the cost associated problem, quadratic assignment and the inverse assignment. Furthermore, about the solution methods, the Hungarian algorithm is one of many algorithms that have been devised that solve the linear assignment problem within time bounded by a polynomial expression. Other algorithms include adaptations of the primal simplex algorithm, and the auction algorithm. See Burkard et al. (2012) for a complete review of the assignment problems. The next section presents the state of the art of current applications of the use of simulation and optimization together.

Therefore, the methodological approach in the present research is based on the preceding concepts, used for solving a problem in the context of the metalworking industry. This approach is summarized in Figure 1.



Figure 1. Methodological approach

### 3. LITERATURE REVIEW

As simulation has been one of the most important available methodologies to investigate systems behaviour, nowadays it is extensively used as a cutting edge technology in critical sectors as defense, airspace, industry and supply chain (Longo, 2011).

Smith (2003) resumes 30 years of simulation applications. In his survey, he reviews and classifies literature on the use of discrete event simulation for manufacturing systems design and operation problems. Similarly, the recent survey published by Jeon and Kim (2016) presents the state of the art of simulation modelling techniques in production planning and control (PPC), from 2002 to 2014. The authors classify the applications reviewed in three types of simulation techniques (system dynamic, discrete event simulation and agent-based simulation) and eight PPC issues (facility resource planning, capacity planning, job planning, process planning, scheduling, inventory management, production and process design, purchase and supply management).

Some of the most recent applications described in literature on assignment problems in supply chain and industry include the work of Ruiz et al. (2012), who proposes a decision-making model that optimizes allocation of demand across a set of suppliers considering expected losses associated with delivery defaults, purchasing costs, unforeseen costs of nondelivered supplies, and supplier management costs. Pérez Becerra (2006) develops a generic model for assigning orders to a set of machines, also applicable to the assignment of workers or materials. Salazar et al. (2013) propose a two-phase approach based on quadratic-quartic assignment and AHP (Analytic Hierarchy Process) as an integrated methodology in flexible manufacturing environments to solve the problem of cell formation and facility layout in the metallurgical sector. Medina et al. (2009) use heuristics for solving the problem of forming lots in a flexible manufacturing system, for a specific assignment of operations and tools to machines.

Finally, it is interesting to review some of the most recent researches that use simulation and optimization together as complementary methodologies. Many applications of this type found in literature are related to the chemical industry, for instance the work of Scenna et al. (1999), Puigjaner et al. (2006), and Rodríguez et al. (2005). Also in finance there are many applications like portfolios selection (Torres, 2004) and development of financial models (Gutiérrez Carmona, 2008). Other applications include the simulation and optimization of a gas separation and stabilization factory (Pan-Echeverría et al., 2009), a coloured Petri net based methodology for the optimization of logistics systems through simulation (Narcizo et al., 2005), the optimization of clinical trials of medication by means of simulation of discreet events (Monleón, 2005), and the development of an air-cooled high efficiency absorption machine for its use in cooling houses or transportation vehicles, such as trucks, busses or boats (Marcos, 2008). Fu, Glover and April (2005) describe the most important approaches in the use of simulation and optimization together, proposing a multi-category classification framework and a survey on related software available.

In the local context of the Mexican industry, where the present study takes place, simulation and optimization have been used in industry and logistics applications like vaccines distribution (Lara, 2016), supply chain optimization (Villareal, 2011), optimal ambulance allocation (Vindel, 2015) and production planning (García, 2013).

# 4. THE SIMULATION AND OPTIMIZATION MODEL

Following the simulation methodology, the performance of the pressure welding workstation was conceived in the conceptual model shown in Figure 2. This preliminary model was validated in the facility with the production and engineering teams, concluding that the model is an appropriate representation of the real workstation performance.

Foils and other parts that are to be assembled are stored in a materials warehouse. The workstation is nearby the warehouse, so the supply of material can be considered immediate. The complete demand of one part is provided in small quantities from the warehouse to the workstation. Each kind of part supplied to the workstation must specify the machine to be used, as machine settings are specific for each part. The ten machines can work simultaneously. As an important assumption for the simulation, a generic batch of product is considered to be a unique entity, which has the associated attributes "kind of product" and "batch size". The latter corresponds to the demand of the part. Therefore, considering a project that consists of processing 10 parts, the production cycle ends when all ten batches are processed (one batch per part). One production cycle corresponds to one run in the simulation.

In order to determine the probability distributions of the machine productivities needed in the model programming, 3 months of historical data for the manufacturing of similar parts was used. The main measure of interest is the productivity of each machine, which is to be analyzed in different feasible scenarios for the machine configuration. Another important performance measure is the average batch time of the system, which permits to validate the model through a comparison test for population means. It is also necessary to review the overall operation time in each scenario, as earnings increase when this time is minimized.

Once all interested parties validated and accepted the conceptual model, simulation model programming took place with the PROMODEL® software, installed in a Samsung Serie 7 Chronos laptop with an Intel Core i5-3210M CPU 2.50 GHz processor. Eleven locations were used (10 welding machines and 1 materials





warehouse), one entity (product batch), five attributes (3 for the entity and 2 for the operation locations), eighteen variables, 12 resources (10 machine operators and 2 setup operators), one external file (work shift), and transversely the programming logic according to the author's approach and experience.

Each probability distribution included in the model associates an independent chain of random numbers tested on independence, homogeneity and goodness of fit, using software StatFit®. Facility's work shifts were designed using PROMODEL's Shift Editor, a complementary tool that generates an external *.sft* file linkable to the model through the shift assignments function.

Verification of the programmed model permitted to review its correspondence with the proposed conceptual model and its assumptions, and if the study objectives in the facility were being achieved. Additionally, the simulated average batch time in the system was tested against historical data for the statistical validation of the model. For historical data, sampling standard ANSI.ASQC Z1.4 was used to establish the sample size required for the test, bearing in mind a general level II inspection (ANSI, 1993). For model data, the number of replications was used as the sample size. The number of replications was determined by means of the expression (1):

$$n = \left(\frac{t_{(n-1,\alpha/2)}S}{e}\right)^2 \tag{1}$$

where  $t_{(n-1,\alpha/2)}$  is the critical t-student value for n = 10and  $\alpha = 0.05$ , the size of a preliminary sample and the significance level, respectively. *S* is the standard deviation of the preliminary sample and *e* is the estimation error margin defined by the engineering and production teams of the facility. The number of replications was determined to be 15 while the historical data sample size was 20. A *t*-test for comparison of population means was applied assuming corresponding variances as unknown and different. Table 1 presents the test results; sample averages are given in working days.

	FACILITY	MODEL
Average	44.900	43.533
Variance	215.989	28.838
Observations	20	15
Degrees of freedom	25	
t statistic	0.383	
	0.352	
P(1 < -1), one queue	1.708	
Critical value of t (one queue)	0.704	
P(T<=t), two queues	2.059	
Critical value of t (two queues)		· ·

 Table 1. Test t of means for two samples assuming unknown and different variances

As the absolute value of the *t*-statistic is lower than the critical *t*-value, there is no statistical evidence that the population means of historical and simulated data are different, so they are assumed to be equal. In conclusion, the simulation model can be considered a valid representation of the welding workstation.

In the second stage of the study, the linear programming model proposed for optimizing the overall operation time, is defined in terms of a binary variable  $x_{ij}$  that equals 1 if the *i*-th part is assigned to the *j*-th machine, and equals 0 in any other case, as follows:

Minimize 
$$Z = \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{d_i}{c_{ij}} x_{ij}$$
(2)

Subject to:

$$\sum_{i=1}^{m} x_{ij} = 1 \tag{3}$$

$$\sum_{j=1}^{n} x_{ij} \le 2 \tag{4}$$

where  $c_{ij}$  is the productivity of the *j*-th machine to process the *i*-th part, simulated in the first stage of the study,  $d_i$  is the demand required for the *i*-th part, *n* is the number of welding machine in the workstation and *m* is the total amount of parts to be manufactured. Expression (3) is the constraint that ensures that the complete production of one part is assigned to only one machine, and the constraint given in expression (4) ensures that the production of maximum two parts is assigned to each machine, as required in the facility. In cases where the assignment is restricted because not every machine j can process every part i, the corresponding machine productivity  $c_{ij}$  is a huge value assigned randomly.

### 5. EXPERIMENTS AND RESULTS

Reproducing in the simulation model the production scheme according to presently observed assignation rules based on experience, the machine productivities obtained are in a range between 1.67 and 5 units per minute, with an average of 2.64 units per minute; this scenario is called the *present situation*. The minimum overall operation time obtained for this scenario is 3643 man-hours, which corresponds to 405 working days, bearing in mind one daily shift, as required by the facility.

The facility was interested in analyzing different scenarios to configure the welding workstation for the production of the ten parts considered. On one hand, a new supplier of welding molds offered a different configuration, increasing in 20% the productivity of machines S-58 and S-67 but also decreasing in 50% the productivity of machine S-78. On the other hand, the engineering team was considering taking a guiding tool from machine S-84 and installing it on machine S-82, so more screws could be fixed per unit in machine S-82, which would increase its productivity in 33% but would also decrease the productivity of machine S-84 in 50%. The facility considered a third alternative, combining both supplier and engineering staff proposals. These three feasible scenarios were analyzed in the simulation model by adjusting the parameters in the corresponding probability distributions. The summary of the scenarios is presented in table 2.

Scenario	Increase (%)	Machines	Decrease (%)	Machines
Supplier proposal	20%	S-58, S-67	50%	S-78
Engineering proposal	33%	S-82	50%	S-84
Combined proposal	20%,	S-58, S-67	50%	S-78, S-84
	33%	S-82	30%	

Table 2. Feasible scenarios for workstation configuration

Table 3 summarizes the estimations of the machine productivities obtained by simulating the present and the proposed scenarios. The range and average values observed for all machines and all replications are presented.

Scenario	Productivity range (units /min)		Average machine productivity	
	Min	Max	(units /min)	
Present situation	5	1.67	2.64	
Supplier proposal	6.25	1.67	2.67	
Engineering proposal	5	1.25	2.50	
Combined proposal	6.25	1.25	2.52	

Table 3. Machine productivities: range and average

These results are illustrated in figure 3. The scenario proposed by the new supplier implies the largest range of machine productivity, as well as the maximum average.



Although optimal productivity is achieved for the supplier proposal, average batch time and overall operation time were not considered in the corresponding analysis. An additional analysis based on these performance measures was carried out to be able to decide which is the best scenario. The overall operation time and the average batch time obtained for the present situation and the feasible scenarios are presented in table 4, both in man-hours and working days. The same information is presented graphically in figure 4.

Scenario	Overall operation time		Average batch time	
	man-hours	working days	man- hours	working days
Present situation	3643	405	364	40
Supplier proposal	3581	398	358	40
Engineering proposal	3537	393	354	39
Combined proposal	3581	398	358	40

Table 4. Overall operation time and batch averaged time in system



As figure 4 shows, the optimal overall operation time is obtained in the scenario proposed by the engineering team, which achieves a minimum of 393 working days

for the complete production of the 10 parts. Therefore, this alternative represents the best savings for the facility.

Although the facility considered the combination of the supplier proposal with the engineering proposal as an

enhanced scenario, the assignment model demonstrates that the overall operation time obtained in the mixed scenario is the same as the time obtained in the single supplier proposal. The engineering proposal implies a minimum overall time, and it is cheaper to carry out. Additionally, even though the supplier proposal involves the highest machine productivity of all proposed scenarios, the best alternative for the welding workstation is the machine configuration suggested by the engineering team due to the best performance of the overall operation time, even while machine productivity was the lowest in this scenario. These results are complemented by the performance of the average batch time in the system (figure 5), which has a minimum value of 39 days for the engineering proposal.



Figure 5. Average batch time in the system

As the average batch time in system corresponds to a central tendency measure, its value is found to be very similar for the different scenarios; still, it presents an optimum value in the engineering proposal, corroborating this scenario as the best choice for the facility.

### CONCLUSIONS

The present simulation and optimization study in the metalworking facility conducted successfully to a simulation model that represents the pressure welding workstation's behavior, and an assignment model that optimizes the most relevant performance measures for the facility. The combination of simulation and optimization offers important quantitative and qualitative technical criteria for the facility's decision making.

The present situation in the welding workstation revealed a non-optimal assignment of the production requirements, because the assignment planning was based only on empirical knowledge. The proposed methodology permitted identifying the assignment scenario that offers the best benefits to the facility.

With the successful culmination of this project, the advantages of using simulation were confirmed, as the cost associated with this simulation and optimization study is lower than the cost for implementing the scenarios in the real system.

#### REFERENCES

- ANSI 1993. Sampling procedures and tables for inspection by attributes ANSI.ASQC Z1.4-1993. Wisconsin: American national standard institute -American society for quality control.
- Brualdi R., 2006. Combinatorial matrix classes. Encyclopedia of Mathematics and Its Applications 108. Cambridge: Cambridge University Press.
- Burkard R., Dell'Amico M., Martello S., 2012. Assignment Problems. Revised reprint. Society for Industrial and Applied Mathematics.
- Fu M.C., Glover F.W., April J., 2005. Simulation optimization: a review, new developments, and applications. Proceedings of the 37th Winter Simulation Conference, pp. 83-95. Dic 4-7, Orlando (FL, USA).
- García J.A., 2013. Metodología para la planeación de la producción utilizando simulación y programación entera. Magister dissertation. Universidad Nacional Autónoma de México.
- Gutierrez Carmona, J., 2008. Modelos financieros con Excel. Bogotá. 2a Ed. Colombia: Ecoe Ediciones.
- Jeffus L., 2011. Welding: principles and applications. 7th Ed. Delmar, USA: Cengage Learning.
- Jeon S.M., Kim G., 2016. A survey of simulation modeling techniques in production planning and control (PPC). Production Planning and Control, 27 (5), 360-377.
- Lara J., 2016. Simulación y optimización para una estrategia de distribución de vacunas contra la A(H1N1). Magister dissertation. Universidad Nacional Autónoma de México.
- Law A., 2015. Simulation Modeling and Analysis. 5th ed. Boston: McGraw-Hill.
- Longo F., 2011. Advances of modeling and simulation in supply chain and industry. Simulation, 87 (8), 651-656.
- Marcos J.D., 2008. Prototipo de máquina de absorción de LiBr/H2O de doble efecto condensada por aire. Simulación, optimización y resultados experimentales. Doctoral dissertation. Universidad Carlos III de Madrid.
- Medina P.D., Cruz E.A., Restrepo, J.H., 2009. Problema de formación de lotes de fabricación en un sistema de manufactura flexible: Heurística de selección de partes. El Hombre y la Máquina, 32, 68-75. Universidad de Barcelona.
- Monleón T., 2005. Optimization of the clinical trials of medicaments by means of simulation of discrete events, modeling, validation, monitoring and the improvement of the quality of its information. Doctoral dissertation. Universidad de Barcelona.
- Narciso M.E., Piera M.A., Figueras Jové J., 2005. Optimización de sistemas logísticos mediante simulación: Una metodologia basada en redes de Petri coloreadas. Revista iberoamericana de automática e informática industrial, 2(4), 54-65.
- Pan-Echeverría G., Gaumer-Araujo T., Pacho-Carrillo D., 2009. Simulación y optimización de una planta de separación y estabilización de gas y

condensados. Tecnol. Ciencia Ed. (IMIQ), 24 (1), 66-75.

- Pérez Becerra J.A., 2006. Modelo de asignación aplicado a la manufactura en una cadena de abastecimientos, Bachelor dissertation. Universidad Mayor de San Marcos, Perú.
- Puigjaner L., Ollero P., De Prada C., Jiménez L., 2006. Estrategias de modelado, simulación y optimización de procesos químicos. Madrid: Editorial Síntesis.
- Rodríguez S.L., Vega Granda, A.B., 2005. Simulación y optimización avanzadas en la industria química y de procesos: HYSYS. Oviedo: Universidad de Oviedo.
- Ruiz Torres A.J., Ablanedo Rosas, J.H., Ayala Cruz J., 2012. Modelo de asignación de compras a proveedores considerando su flexibilidad y probabilidad de incumplimiento en la entrega. Estudios gerenciales, 28 (122), 29-48.
- Salazar A.F., Vargas L.C., Añasco C.E., Orejuela J.P., 2013. Propuesta de distribución en planta bietapa en ambientes de manufactura flexible mediante el proceso analítico jerárquico. Revista EIA, 7(14), 161-175.
- Scenna N.J., Aguirre P.A., Benz S.J., Chiotti O.J., Espinosa H.J., Ferrero M.B., Montagna, J.M., Mussati M.C., Pérez G.A., Rodríguez J., Salomone H.E., Santa Cruz A.S.M., Tarifa E.E., Vega J., 1999. Modeling, simulation and optimization of chemical processes. Argentina: Universidad Tecnológica Nacional.
- Smith J.S., 2003. Survey on the use of simulation for manufacturing system design and operation. Journal of Manufacturing Systems. 22 (2), 157-171.
- Torres C.L.M., Munera J.A.R., Henao, J.D.V., 2004. Selección de portafolios usando simulación y optimización bajo incertidumbre. Dyna, 71 (141), 35-57.
- Villareal J.E., 2011. Simulación y optimización de la cadena de suministro con programación lineal entera mixta. Magister dissertation. Universidad Nacional Autónoma de México.
- Vindel J.A., 2015. Localización óptima de ambulancias en Ciudad Universitaria empleando simulación. Magister dissertation. Universidad Nacional Autónoma de México.

## AUTHORS BIOGRAPHY

Fabio Daniel Chaves Almanza is an industrial engineer from the National University of Colombia, Bogotá, in 2006, and he received the degree as Production and Logistics Engineering Specialist from the Districtal University "Francisco José de Caldas", Bogotá, Colombia, in 2013. He has achieved 10 years of career in the field of management systems, in private and public sectors. Actually he is a graduate student in Industrial Engineering at the National University of Mexico (UNAM) in Mexico City. Ann Wellens is a chemical engineer with postgraduate studies in Industrial Administration (KUL, Belgium) and a master degree in Environmental Engineering (UNAM, Mexico). At the moment she is a full-time lecturer in the Systems Department of the Industrial and Mechanical Engineering Division of the National University of Mexico (UNAM). She has been working in air pollution issues for the last 15 years, dictating courses, collaborating in research projects and participating in conferences related with mathematical modelling of air pollution dispersion and statistics.