Design of production systems using computer modelling of human-robot interaction

A Kampa, G Golda and D Konysz
Silesian University of Technology, Faculty of Mechanical Engineering, Institute of Engineering Processes Automation and Integrated Manufacturing Systems, Konarskiego 18A, 44-100 Gliwice, Poland
E-mail: adrian.kampa@polsl.pl

Abstract. Designing a production system is a complex process that requires many factors to be taken into account, including the interaction between a human and a machine. The industrial robot is a specific type of a handling machine, which can work similarly to a human, and can be used in different areas in a factory. Therefore, there is a need to consider all important human and robotic factors early in the manufacturing process and industrial system design. Especially the computer simulation of the production processes with the use of Discrete Event Simulation method, carried out for the needs of a new project, allows us to already include the process flow at the industry system planning stage, before real implementation. The purpose of this work is developing a framework of a digital twin of a manufacturing system. An example of a newly designed manufacturing system for the production of elements from the automotive industry is presented, as well as simulation models developed in the FlexSim program, which enables predefined parameterized objects for humans and robots. An area requiring improvement was defined, and the possible effects of these actions on the overall process were reengineered, considering the parameters of availability, performance, quality, and failure rate that make up the OFE (Overall Factory Effectiveness) metric. The information obtained during the simulation allowed us to define the location of the bottleneck in the process, and thus determine what to focus on during the implementation of the manufacturing line. In the future, the models will be expanded in perspective of using the digital twin in Industry 4.0.

1. Introduction
The current concepts of project management in the field of production processes organization are striving to minimize design changes in phases occurring later than the planning phase, thanks to which savings are achieved (because the costs of introducing modifications to the design increase with the advancement of work on it). Traditional design gets conducted in a series. Each next task starts when the predecessor ends. Carrying out a project this way significantly extends the time of its implementation, as well as increases the risk of mistakes being made at particular stages of design due to limited communication. The concurrent design increases the likelihood of detecting critical points early in the process [1]. That is also related to the concept of front-loading [2], which consists of introducing changes at the beginning of the project and verifying the project at an early stage. That way, the largest number of necessary modifications is introduced at the planning stage, when the cost is the lowest. During the feasibility phase of a project, savings of about 20-40% of the total costs of this phase are possible [3]. Verification of the project assumptions at an early stage is possible with the use of modelling and computer simulation methods. The simulation gets performed on a model that is
physically or mathematically equivalent to an object or event in a real system [3]. The model is a simplified version of reality, usually limited to the elements necessary for the experiment. Simulations get widely used in the field of production, which is a complex system of people and machines interacting, because researching real systems is often impossible or unjustified economically. Simulations are widely used to test new concepts, verify designs, and monitor progress. Simulations allow for presenting the project assumptions transparently to a wider audience, thus allowing more people to be involved in the early phase of the project. A diverse audience increases the probability of detecting and modifying weak points in the early phase of the project when their modification is the cheapest [3]. A simulation created to solve a problem is a project with its own life cycle. There are five stages in the simulation life cycle: goal definition, modelling, analysis, implementation, and evaluation of results. The process begins with understanding the model, followed by the model building phase, followed by the checking part. The results obtained by the simulation are entered into the action plan [3].

One of the problems is simulating the work of operators, in which the specificity of human work should be taken into account. The human factor is characterized by considerable variability and human errors, which, in principle, are impossible to predict, and may contribute to the disorganization of the production process. Due to the individual characteristics of each person, it is troublesome to introduce strict parameters defining the operator's work into the model. The most common is the averaging of operating parameters in the form of a time standard or a set time [4]. Because of instability of human operated processes, the industrial robots are often used especially for repeatable and monotonous activities. Therefore, the collaboration of humans and robots should also be taken into consideration [5]. Typically, simplified models of manufacturing systems, which give an approximate representation of reality, are used. More detailed models are difficult to build and analyse, but they can give better results [6]. Especially the category of advanced models known as “digital twin” [7], offers many possibilities of use including reducing costs, risk and design time, complexity and reconfiguration time; improving after-sales service, efficiency, maintenance decision making, security, safety and reliability, manufacturing management, processes and tools; enhancing flexibility and competitiveness of the manufacturing system [8]. For the effective operation of the digital twin, all elements of the production system structure must be mapped, including the human operator, which can also be digitally modelled [9]. Therefore, the purpose of this work is developing a framework for a digital twin of a manufacturing system. In the future, models will be expanded depending on the life cycle of the production system and the industry 4.0 perspective.

2. The description of the problem

The management board of the company dealing in the production of automotive components has decided to launch a new production line in one of the plants in Poland [10]. The production line was dedicated to the production of one product reference. Initial findings included a production line consisting of one automatic welding machine, two calibrators, three welding robots, as well as leakage testing and geometry control. The manufacturing process consisted of seven operations presented in table 1.

Preliminary analysis of the time required to complete each operation showed that the stations would have to be partially automated, and three operators should be enough to run the line without loss of efficiency. The assignment of operators to workstations is as follows:

- Operator 1: OP10, OP20, OP30,
- Operator 2: OP40, OP50,
- Operator 3: OP60, OP70.

Figure 1 shows the planned location of the stations together with the assigned operators. Machines OP10, OP40, OP50 are equipped with two windows in which the components are placed and connected with the welding robots. While the operator fixes the components on one window, the welding process takes place on the other. As a result, the welding process of the robot is not interrupted by the time the operator manipulates the workpiece.
Table 1. The description of the production process [10].

| Operation | Description |
|-----------|-------------|
| OP10      | Welding the inlet cone with the flange and the outlet cone |
| OP20      | Welding of sleeves for the inlet cone and body |
| OP30      | Calibrating the inlet diameter of the inlet cone and the inlet and outlet diameters of the outlet cone |
| OP40      | Circular welding of the inlet and outlet cone to the body |
| OP50      | Welding of pressure pipes and brackets |
| OP60      | System tightness check |
| OP70      | System geometry control |

Figure 1. Initial layout of material flow and operator movements [10].

The first operator places the inlet and outlet cones on the OP10. Then they place the inlet cone sleeves and the body on the OP20, from where they take the welded body. Afterward, the operator feeds it to the OP40 and goes with the cone to the OP30. On the OP30, it calibrates the diameter of both cones, which also passes on to the OP40. Operator 2 mounts a cone and body system on the OP40, then adds tubes to the system and supports on the OP50 and places it on the OP60. There, the operator 3 performs a leak test (OP60), a geometry check (OP70) and then packs the product ready for shipment.

3. Modelling and simulation in FlexSim

The FlexSim Simulation Software package enables modelling of real-life systems and discrete-time simulations with visualisation in 3D technology, including virtual reality experience.

When creating the simulation, the time of operations performed by employees was based on MTM-UAS (Methods-Time Measurement – Universal Analysing System) analyses [4], and machine cycle times based on technological data have been taken into account. Additional information on the causes
and duration of machine downtime was determined based on existing, similar production processes that served as a reference for the simulation. To avoid excessive complexity of the simulation and thus to make the simulation results more readable, the following simplifications were introduced. All components and blanks in the process have been replaced with a single element that determines the sequence of material flow in the process. The robot stations were modelled in the form of two machine-type objects. One of them is responsible for the simulation of loading by the operator, the other for the simulation of the automated process.

The time needed to load the components in the machine and start the machine, as well as for all operator movements, was calculated based on the MTM-UAS analysis [11]. This statistic was introduced into the model as the setup time per one workpiece. To simulate the variability of the operators' work, a normal distribution was used with the mean value and standard deviation. In turn, the machine cycle times (processing time) were determined based on technologic data. The assumed production capacity is at least 180 pieces per shift, with 7.25 hours of effective working time. The constructed model is shown in figure 2.

![Figure 2. Model of the production system in FlexSim software [10].](image)

The process time values for subsequent operations are presented in table 2,

| Operation | Setup time [s] | Stand. Dev. [s] | Processing time [s] |
|-----------|----------------|-----------------|---------------------|
| 10        | 41             | 2               | 108                 |
| 20        | 31             | 2               | 20                  |
| 30        | 0              | 0               | 29                  |
| 40        | 44             | 2               | 120                 |
| 50        | 56             | 2               | 100                 |
| 60        | 44             | 2               | 60                  |
| 70        | 0              | 0               | 60                  |
Table 2 includes the mean value and standard deviation of a normal distribution, for setup time. The standard deviation was obtained from the time study of similar processes [10]. The processing time of the machine was based on technological data.

The next step was to introduce planned downtime on the line. The downtime consisted of:
- 5 minutes at the beginning of the shift, for the work organization,
- 30 minutes break in the fourth working hour,
- 10 minutes at the end of the shift dedicated to cleaning the workstation.

4. Simulation experiment
The duration of the simulation scenario was set to 8 hours of work, which is one shift. After entering the data, simulation no. 1 was conducted to determine the maximum production, which is not affected by any disruptions and no downtime other than planned. The average efficiency of the line was 219 pcs/shift with the calculated maximum efficiency of 238 pcs/shift, the obtained OFE (Overall Factory Efficiency) index [12] was 92%. The high result was caused by no quality losses or failures included in the first simulation. The collective simulation results are presented in table 3.

The model was supplemented with a simulation of machine downtime by adding failure rates. For the purposes of the simulation, the definition of failure was extended, including machine downtime caused by adjustments to welding parameters and replacement of the welding machine consumables. Two scenarios of machine downtime and a case of unplanned downtime (failure) of operators were created. For OP10, OP20, OP40, the mean time to failure was calculated as MTBF1 (Mean Time Between Failures) = 3600s exponentially. The time range from the start of failure to machine restart was set to MTTR1 (Mean Time To Repair) = 300-900s in uniform distribution. The second scenario concerned the OP50 as a machine more prone to downtime. The reason for this decision was the high complexity of the machine, a greater number of welded parts of the product, and high loads on the machine mechanisms caused by the weight of its elements. Therefore, the MTTR1 was determined in the range of 300-1800s. The failure rate was defined for employees based on photos of the working day MTBFp = 3 hours and MTTRp = 600-1020 seconds.

To supplement the simulation with the possibility of a formation of scrap pieces at the OP70 output, a rule to send products to warehouses was introduced. As a principle, products leaving the operation had a 95% chance of being placed in the finished product warehouses and a 5% chance of being placed in the defect zone. The proportion of scrap was determined based on a process similar to the one described.

During simulation no. 2, which covered 8 hours of work, on average 178 good-quality finished products were produced, which constitutes 75% of the maximum efficiency of OFE and nine defective ones. The analysis of the machines’ operation showed that the bottleneck in the process is the OP50.

As the obtained line efficiency was lower than the assumed capacity by two pcs/shift, the technology department analysed the FMEA (Failure Mode Effect Analysis) in terms of elimination of the causes of failure. Based on this analysis, the failure rates for OP50 were changed. After making changes, the parameters influencing machine downtime are as follows: MTBF3 = 3600s, MTTR3 = 300-1300s. The analysis also showed the possibility of reducing the maximum duration of the failure of the OP40 robot from 900s to 600s. Therefore, simulation number 3 was performed.

Table 3. Summary of simulation results: Pavg- average production in pieces [pcs] per shift 8h, Pmin - minimum production, Pmax maximum production, Plimit - production limit under ideal conditions, LL-lower limit, UL- upper limit, 95% confidence level, 20 simulation runs [10].

| Simul. No | Pmin [pcs] | LL [pcs] | Pavg [pcs] | UL [pcs] | Pmax [pcs] | Std. dev. [pcs] | Plimit [pcs] | OFE  |
|-----------|------------|----------|------------|----------|------------|----------------|-------------|------|
| 1         | 210        | 217.8    | 219.3      | 220.7    | 224        | 3.8            | 238         | 0.921429 |
| 2         | 167        | 176.0    | 178.4      | 180.9    | 191        | 5.3            | 238         | 0.749580 |
| 3         | 178        | 186.3    | 188.2      | 190.1    | 197        | 4.9            | 238         | 0.790756 |
During simulation no. 3, an average of 188 pieces of the finished product was obtained within 8 hours, thus achieving 79% of the maximum efficiency. During the simulation, ten units more than during the previous simulation have been produced, and eight units more than the required 180, obtaining additionally nine scrap items.

5. Conclusions
We can observe increasing interaction between virtual and physical spaces, through emerging IoT solutions and Big Data analysis with computer simulation. The use of advanced simulations allowed us to verify the designed production line in terms of possible production efficiency problems. The possibility of emulation of a shop-floor control system and connectivity of simulation models combined with optimisation features and SQL databases access makes FlexSim a promising choice for prototyping and experimenting with the digital twin concept. The next stage may be to supplement the simulation with the data base including expected volumes of orders on a weekly or monthly basis, which would allow us to determine the required level of production, both short and long term. Therefore, the direction of further research includes modelling and simulation of digital twins in the perspective of Industry 4.0.

6. References
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