EXPERIMENTAL MANUFACTURING SYSTEM FOR RESEARCH AND TRAINING ON HUMAN-CENTRED SIMULATION

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ABSTRACT

Human performance modelling and simulation requires a multidisciplinary approach for a full understanding of its effects in manufacturing. These areas broadly span production theory, behavioural science and ergonomics. In despite of the advances in each one of them separately, few papers have adopted a global-scope approach. Previous works have mainly focused on the integration of models coming from the different disciplines involved. This paper presents the design and construction of an experimental manufacturing system which allows for conducting research and training on human operations analysis within a controlled environment. Task procedures, supervisory mechanisms and data acquisition systems are arranged so that non desirable variability is restrained to an acceptable level. System architecture was inspired by virtual simulators enabling results analysis in a structured way. The system provides with capability for experimentation in interaction of behavioural and ergonomic effects, model validation research and teaching in simulation and other process improvement tools.

Keywords: human-centred simulation, modelling and simulation of human behaviour, ergonomics.

1. AIM AND PREVIOUS RESEARCH

Flexibility provided by labours is one of the major reasons usually argued for not automating manufacturing operations, especially in expensive labour markets in which cost based decisions may not support this argument. Different production environments can be found in which human work characteristics such as adaptability, responsiveness or learning cannot be efficiently substituted by machines.

In addition, a variety of production circumstances -high product variability, small batches production, customizable design or short product life cycles, among others- require a production line to be easily reconfigured in order to reduce setup costs.

Low inventory systems are another type of systems highly sensitive to variation (Schultz et al. 2003). Flexibility provided by labours is one way of counteracting this drawback and enabling gains from lower inventory costs to be effectively realized. Indeed, self-regulated labours work-pace is the main cause found by Shultz et al. (1999) to explain the empirical observation presented in previous works (Schonberger 1982): low inventory systems with manual operations do not present as large throughput loses due to blocking and starvation as expected from an analysis in which human performance is modelled in a mechanistic way.

Assembly and disassembly are other production areas that largely rely on human involvement due to high investment costs in automation (Bley et al. 2004). These authors also refer to flexibility and reconfigurability as mandatory needs for ensuring competitiveness within an environment of growing demand on product variety and shortening lot sizes.

Traditionally, analysis of production systems has been mainly focused on technical aspects such as machines, buffers or transportation elements (Baines and Kay 2002). Human resources are introduced in the same way as machines and variation sources related to ergonomics or behaviour are ignored (Neuman and Medvo 2009). However, evidence supports that human performance variability differs from that of machines in several ways (Powel and Shultz 2004). Humans behave as state-dependant resources with the capability to readjust their work-pace depending on the circumstances. Also dynamic changes in the working rate are related to factors such as experience, aging, time of day and other external factors (Baines and Kay 2002). Although processing rates of machines might be satisfactorily modelled by their cycle time and failures distributions, a detailed model of human performance should include both dynamic and state dependant effects. Baines et al. (2004) show how simulation results change once certain dynamic effects are taken into account. Powel and Shultz (2004) demonstrate how a flow line performance depends on the presence of self-regulated behaviour.

Knowledge from ergonomics and behavioural science should be incorporated into traditional operations research models for a proper modelling of human factors. In spite of intensive research has been conducted in each one of these areas separately, their interface with operations research has received less attention in the literature; several authors call for further research to be conducted (Neuman et al. 2006, Schultz et al. 2010).

The majority of the papers published so far deal with the integration of models from either ergonomics or behavioural science. For instance, Neuman et al. (2009) have incorporated factors such as operator's autonomy for resting, individual differences and operators capacity in a discrete events simulation experiment. Their results show significant effects on throughput based on variability levels. Elkosantini and Gien (2009) and Riedel et al. (2009) have incorporated cognitive models for labours decision making in simulation models. These authors conduct feasibility studies and provide guidelines on how to implement them. However, they both point out the need to study the effective actual application of their approaches to real cases as well as the necessity of a proper model validation.

Another approach found in the literature is the execution of experiments in laboratory manufacturing settings. Laboratory experimentation is a common research tool in behavioural science, although we have been able so far to find only three papers that adopt this approach when studying the interaction between technical and behavioural elements in manufacturing. Schultz et al. (1998, 1999, 2003) executed experiments on human performance effects in low inventory systems and work-sharing. They arranged a laboratory flow line that consisted of three serial operations. The tasks consisted of introducing codes in a software application representing customer orders. Experiment subjects were high school students. Another experiment is presented in the paper of Bendoly and Prietula (2008). In this case the process consisted of a single operation in which subjects had to solve TSP instances by means of a software application. Subjects were recruited among students in a business school and thus they had a different profile compared to those in the Schultz's experiment. In both cases the tasks have only a mental workload. Physical workload is negligible, what makes an outstanding difference with many manufacturing environments.

In this paper we present a system designed for conducting research on the effects of human variability in manufacturing and for validation of human performance models. The approach consists of arranging an experimental manufacturing setting in which product and process related variability is kept under control. Thus, human resources variability can be isolated and studied in deep. Comparison between the experimental system output and a virtual simulation model allows for analysing the effects on system behaviour and the errors incurred by the modelling approach.

The system can also be applied for training purposes. Realistic simulation case studies can be proposed to students who can take part as either operators or simulation practitioners. Process improvement tools can be tested and put into practice. This method for teaching in simulation has the benefits of learning by doing. Students may develop greater skills for applying simulation tools. They also gain insight into how to properly model a system and how to validate results within a controlled environment in which all the relevant factors can be taken into account.

Section 2 describes the systems conceptual design and elements. Possible variability sources are introduced along with an explanation on how to manage them. Section 3 presents an initial experiment conducted based on a roofing slates manufacturing process. Industrial Engineering students have taken part as operators and simulation practitioners. In section 4 some preliminary results obtained from the experiment are shown and discussed. The paper finishes with some concluding remarks.

2. SYSTEM DESIGN

2.1. The process

The designed process has been inspired by a manufacturing plant that produces roofing slates elements (del Rio Vilas et al. 2009). It is a labour intensive process characterized by high levels of product, process and resources variability. Previous research has shown important individual differences in performance and how productivity gains can be achieved when improving ergonomic conditions (Rego et al. 2010).

The experimental manufacturing process consists of five tasks arranged in a closed loop. Four of them constitute the analysed process and the fifth one is disposed in order to close the loop preventing from recirculating starvation or blocking events. The fifth task is converted into an events horizon by means of a security stock of input parts which would be consumed in case the production output was temporary incapable of providing enough input.

Process input and output products are the same, i.e., lots of a fixed amount of slates. The size of these lots will be noted as N_E. Slates are grouped into three types according to two attributes. A fraction p_R of the slates are printed with a red mark on them and the rest of them (fraction $p_G = 1 - p_R$) with a green one. Green slates are divided into two sizes, large size elements with dimensions 32x22mm and small size elements with dimensions 30x20mm and 27x18mm. These formats correspond to the main commercial formats traded by the company. The fraction of large size slates within green type will be noted as p_L and the fraction of small size type p_S. Green slates also display an alphanumeric code printed on their surface made up by two letters and one number. Input lots contain a sequence of slate types randomly generated according to the proportions defined before. Consecutive realizations of the selected slate type are independent between them.

The first task is the classification of slates according to their colour. It is performed in the so-called workstation 1 (WS1). Classified items are batched into lots of size N_R for red slates and N_G for green slates. Every time that a lot is passed to the next station the operator registers it in a software application called WS1_Register by pressing either the red or green lot corresponding key.

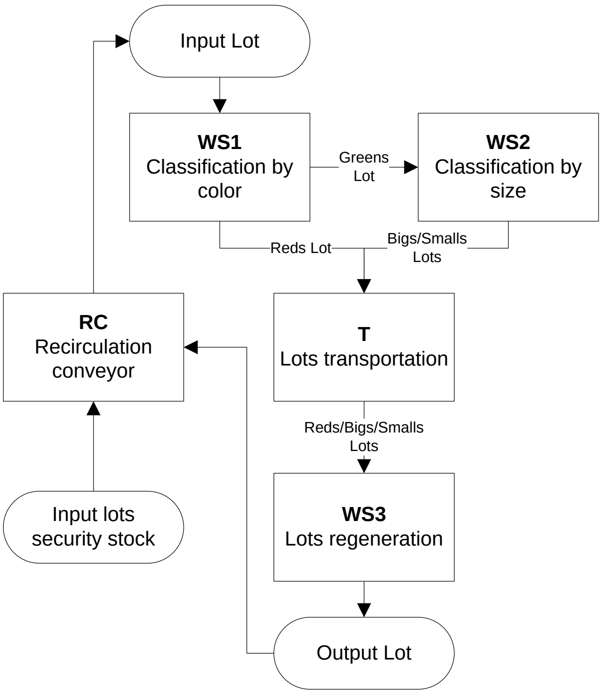


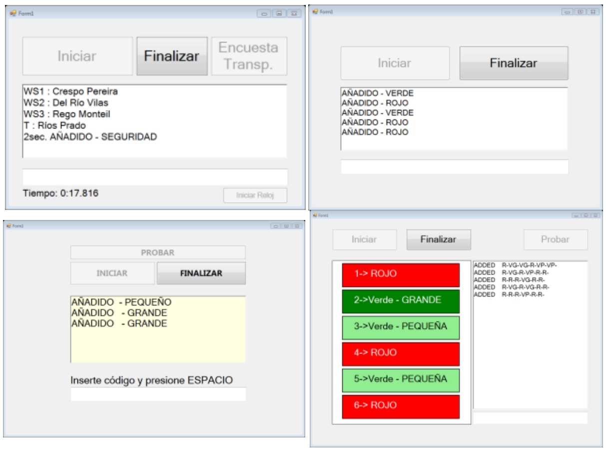
Figure 1: Process diagram.

The second task is performed in workstation 2 (WS2). It consists of the measure and classification of the green slates according to their size. Slates are taken one by one and measured either by means of a reference mark printed on the workplace or at a glance once the operator has acquired experience. Then the slate code is typed on a computer and registered by the application WS2_Register. The slate is finally piled in the corresponding lot upon size. Errors in either typing or classification are penalized so that demand on worker's attention is the highest within the process.

The third task in the process is a transportation one. Classified lots from workstations 1 and 2 are carried up to the workstation 3. A default parking location has been established at an intermediate point between WS1 and WS2 and marked on the floor.

The fourth task has the function of regenerating the input lots for the process. A random sequence of N_E slate types is generated and printed in a monitor by the WS3_Register application. Once a lot is completed it is pushed to a recirculation conveyor which acts as both the source and the sink for the rest of the process. Each time that a lot is pushed, it is registered in the application by pressing a key.

The fifth task is disposed in order to make the WS1 arrival process independent from the WS3 state. Thus the closed loop setting results would not differ from those of an open process. The workplace is functionally equivalent to a conveyor belt in which input lots are moved from WS3 back into the source slot. An auxiliary reserve of input lots is placed beside this station for use in cases of lack of output lots from WS3. It is a supervisory and control oriented stage which plays an important role in standardizing process conditions and restricting undesired forms of variability. Lot arrivals to WS1 are registered in a control application called Source_Register which also provides functions for managing experimental runs such as time control or workers assignments to workplaces. It will not be analysed as part of the process along with the rest of the tasks.



WS1 : Crespo Pereira
WS2 : Del Río Vilas
WS3 : Rego Monteil
T : Ríos Prado
2sec. AÑADIDO - SEGURIDAD

Tiempo: 0:17.816

AÑADIDO - VERDE
AÑADIDO - ROJO
AÑADIDO - VERDE
AÑADIDO - ROJO
AÑADIDO - ROJO

AÑADIDO - PEQUEÑO
AÑADIDO - GRANDE
AÑADIDO - GRANDE

Inserte código y presione ESPACIO

ADDED R-VG-VG-R-VP-VP-
ADDED R-VG-R-VP-R-R-
ADDED R-R-R-VG-R-R-
ADDED R-VG-R-VG-R-R-
ADDED R-R-R-VP-R-R-

Figure 2: Source_Register, WS1_Register, WS2_Register and WS3_Register screenshots.

A process variant was designed by enabling work-sharing between transporter and WS2. When this collaborative mode is enabled, the transporter assists WS2 labour by typing registries on the computer. Then WS2 operator focuses only on classifying and moving slates whilst he dictates the alphanumeric codes to his/her teammate, so that cycle time is severely shortened. Meanwhile work-sharing is taking place, transporter cannot attend transportation orders from WS1 to WS3 and thus a trade-off between these two operation modes is created.

Tasks design was intended to result in different types according to the degree of physical and mental workload. Table 1 shows a characterization performed by the research team members.

Table 1: Tasks characterization

Task	**Physical workload**	**Mental workload**
WS1	Moderate	Moderate
WS2	Moderate	High
T	High	Low
WS3	Moderate	Low

2.2. System layout

The production line was built in the Industrial Engineering laboratory of the Escola Politecnica Superior of Ferrol. Four tables were arranged in line and a fifth one was placed nearby for serving as a security buffer of input lots. Slots were printed on the tables in order to establish fixed locations for working and buffering. Each workstation counts with a computer running the corresponding application. The computers are connected to a LAN so that they can connect to a MySQL server for storing the registered data. Figure 3 shows a floor plan of the setting. Table 2 shows the function of each slot. Number of parts in them is constrained in order to simulate capacitated buffers.

Table 2: Slots in layout

Slot code	Parts Capacity	Function
S1	1 Input Lot	Pick up point for input lots.
S2	1 Input Lot	Input lots pick up point for operating under bad ergonomic conditions.
WS1	1 Input Lot	Working slot for WS1.
RB	1 Reds Lot	Batching of red slates.
GB	1 Greens Lot	Batching of green slates.
GTB	1 Greens Lot	Connection buffer of greens lots.
WS2	1 or unrestricted Greens Lot	Working slot for WS2.
LGB	1 Large Greens Lot	Batching of large green slates.
SGB	1 Small Greens Lot	Batching of small green slates.
RTB	1 or 2 Reds Lot	Reds lots input buffer to transporter.
LGTB	1 or 2 Large Greens Lot	Large greens lots input buffer to transporter.
SGTB	1 or 2 Small Greens Lot	Small greens lots input buffer to transporter.
RR	Unrestricted Red Slates	Buffer of red slates waiting to be recirculated.
RLG	Unrestricted Large Green Slates	Buffer of large green slates waiting to be recirculated.
RSG	Unrestricted Small Green Slates	Buffer of small green slates waiting to be recirculated.
WS3	1 Input Lot	Working slot for WS3.
RC	5 Input Lots	Recirculation conveyor.

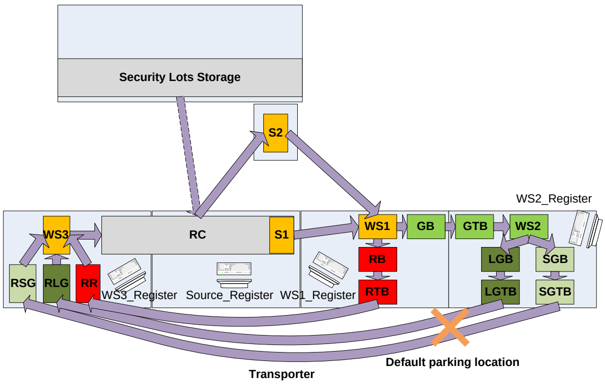


Figure 3: Experimental setting layout.

Figure 4: Experimental Setting in the Industrial Engineering Laboratory.

2.3. Sources of variability

Variability was analysed under a PPR (product, process and resource) approach (del Rio et al. 2009). During the experiment design phase, possible sources of variation were discussed and actions taken in order to avoid non-desirable ones, to control those ones subject of analysis and to trace those considered as non-controllable.

Process variability was limited by defining standardised task procedures which covered the sequence of steps to be performed, the permitted actions and the priorities. Penalties in a reward function together with supervisory mechanisms were put in place. Therefore, operators could not be benefited by deviating from them. The only three exceptions made to this rule were:

1. The transporter was given freedom to choose what lots to prioritize. This was allowed aiming at sampling the different prioritization rules intuitively developed by the subjects.
2. WS2 operators were given freedom on what subtask to perform first: classifying a slate or typing its code on the computer. Although this degree of freedom may increase the effect of individual differences on performance, it is representative of the variability encountered in most of real settings. It also allows the experiment subjects for working in a more comfortable way to them.
3. Under work-sharing enabled, transporter was given freedom to choose when to offer support to WS2 operator and when to stop the cooperation. WS2 operator could refuse the assistance.

However, these sources of variation are human-driven so they will be treated together with the other human resources forms of variability.

Product variability has been intentionally introduced by means of the random composition of input lots. Depending upon their colour, slates flow directly from WS1 into the transporter or they do so through WS2. This sort of variability is present in many real systems that combine the production of products with different processing steps.

This kind of product variability affects line balancing. WS2 task is slower than WS1 in terms of processing time per slate. Hence, when p_R is high, WS1 is the most congested workstation and the low arrival rate of parts to WS2 causes it to have idle times. On the other hand, when p_R is low there are plenty of green slates to be processed in WS2 and since this is a slower task, it causes WS1 to be blocked. Thus, the system bottleneck location will depend on p_R and it can be altered by simply modifying its value. Furthermore, random temporary variations of average p_R will cause the bottleneck to dynamically change from WS1 to WS2 and vice versa. Although this behaviour increases the variability levels of throughput rates – which may cause human-driven variability to be harder to detect –, it is a very desirable feature when analysing state-dependant effects on human performance. Their impact in system performance is expected to be amplified by the higher variability in elements states.

Finally, human resources variability will be the main subject of study within this paper. Several sources of variability were considered taking into account previous published results.

1. Individual differences. Differences in motivation, skills, ergonomic fitness of the workstation among others, cause workers to perform differently when doing the same task. Some basic personal data was gathered in order to search for individual characteristics that might be correlated with performance. Subjects were asked about their age, height, weight, sex and physical activity.
2. Group differences. Interaction among individuals involves complex dynamics which might either favour or disfavour overall performance (Bendoly et al. 2010). As a way of limiting the group effect on performance, subjects were randomly assigned to workstations. This avoided that assignment to position choices distorted the results. However, other forms of group dependant variation could not be accounted for. For instance, the group response to a change in situational pressure might completely differ depending on whether the group is driven by the Abilene Paradox or Group Think (Bendoly et al. 2010).
3. Learning curves. No subject had ever performed this kind of work before. Hence, experience was simply recorded as the number of runs already done by the individual.
4. Time and day of week. Experiment sessions were executed either during the mornings or afternoons. Day of week varied as well. A randomized assignment of treatments to experimental units was expected to counteract its possible effect in the results.
5. Tiredness. The effect of tiredness in performance is a complex issue. It is also a variable hard to measure. Runs duration was set to 12 minutes in order to dispose a level of tiredness affordable by all the subjects. However, the high physical workload caused them to clearly experience it. It was measured by means of surveying at the end of each run.
6. Motivation. Motivational levels are another hard to measure variable. Different levels of effort by individuals were noticed by us during the experiment execution. Some questions in the enquiries were disposed at this purpose.
7. State-dependant behaviour. Analysing state-dependant behaviour requires collecting data of single realizations of task cycle times together with information of the system state. In order to do so, the data acquisition system was designed to report statistics in a virtual simulator-like fashion. By constructing a list of events occurred in the system, its state at each time could be tracked and therefore its relation to task cycle time studied.

2.4. Parameters setup

An initial production run was performed by the research team members as a means of characterising tasks time distributions. This data fed a simulation model implemented in Delmia Quest 5 R20 (Figure 4). The model was then used for adjusting parameters p_R, N_E, N_R, N_G.

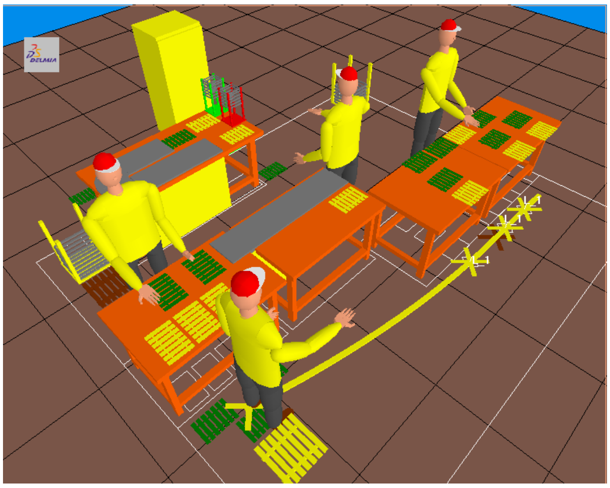


Figure 4: View of the simulation model implemented in Quest.

A solution in which all the workstations had high utilization rates and WS2 was the bottleneck was adopted. WS1 was intended to have a utilization close to WS2 in order to be able to turn it into the bottleneck by a small configuration change. Table 3 and 4 show the adopted configuration and the expected workstations utilization estimated by the model.

Table 3: Process parameters in the adopted solution

Parameter	Value
p_R	60%
N_E	6
N_R	3
N_G	3

Table 4: Process balance estimated by the simulation model (230 runs)

Operator	Utilization
Operator 1	91.74%
Operator 2	96.82%
Operator 3	77.34%
Operator 4	64.81%

3. THE EXPERIMENT

3.1. Subjects

One of the main aspects hampering the possibility of adequately conducting human factors experimentation is in fact the assured and convinced availability of human subjects. Doing so in real manufacturing environments might imply a set of negative consequences in terms of motivation and availability as well as economic and production implications

In this case, the experiment subjects were recruited among Industrial Engineering students of the third year in the Quantitative Methods for Industrial Engineering subject at the Univerisity of A Coruna. The contents of this subject span some common operations research methods such as non-linear optimization, meta-heuristics, queuing theory, discrete events simulation and decision theory. It is the first contact of students with the Operations Research field. Students were offered an alternative evaluation plan to the one traditionally followed consisting of a single final exam. A realistic case study in simulation was proposed for the simulation and optimization of the experimental setting. Students who took part in the activity could get half of their total mark upon the quality of their simulation and optimization analysis and their performance in a final experiment execution rated by means of a reward function. A total of eight teams were formed.

3.2. Design

The experiment was conducted in three phases. First phase was aimed at introducing the subjects to the process and the task procedures. It consisted of a single session of four production runs, each one five minutes long. No information regarding the process was given to them previously. Operators were randomly assigned to workplaces and rotated at each run. Thus all of them had a try on every task and reference cycle times could be computed.

The second phase comprised two sessions of three runs each. Runs were twelve minutes long. The manufacturing experiment was conducted during this phase. Eight teams by two sessions of three runs provided with a total of forty-eight experimental units. Details on the experiment design are given below.

In the fourth session students were evaluated by means of a reward function dependant on throughput rates, work in process levels and errors committed. In this session students could modify selected system parameters: reds proportion (p_R), size of greens lots (N_G), assignment of operators to workstations and capacity of RT, LGT and SGT. Teams were ranked upon score and an additional mark incentive was given accordingly. Duration was set to fifteen minutes.

The experiment factors were selected according to a twofold objective. First goal was to analyse the effect of ergonomics in performance. A single bi-level factor was introduced to this end. Second goal was to study the effect of different manufacturing approaches on behaviour. Four factors were introduced concerning connection buffers size, system state perception, work-sharing and incentives approach. Table 5 shows these factors and their levels.

Table 5: Factors levels

Factor	Reference level (0)	Alternate level (1)
Ergonomics	Good ergonomic conditions in WS1 (Source S1)	Poor ergonomic conditions in WS1 (Source S2)
Inventory	High – Capacity of WS2: ∞, RT: 2, LGT: 2, SGT: 2.	Low – Capacity of WS2: 1, RT: 1, LGT: 1, SGT: 1.
Perception	Full – Operators have visibility of the whole setting	Restricted – A opaque panel is disposed between WS1 and WS2
Work-sharing	Disabled	Enabled
Approach	Throughput – Reward function dependent on throughput rate	Quality – Reward function dependent on errors committed

A full factorial design was dismissed because of the limited number of units available and not all the possible interactions among factors were regarded of interest. Eight treatments were selected aiming at testing the interactions related to the posed hypothesis. They were divided in three areas of interest: ergonomics, technical elements and incentives. Table 6 shows the treatments. Treatment 1 was established as reference treatment for comparison. Treatment 2 was introduced for testing the ergonomic factor effect and treatment 3 for testing the effect of incentives approach. Treatments 4 to 8 concern technical aspects. Due to system balance, combined work-sharing and low inventory settings were dismissed. The setup cost of starting and ending cooperation made work-sharing unfavorable under this circumstances. A complete factorial design was employed for the remaining factors.

Table 6: Treatments

Factor	**Treatment**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Ergonomics	0	1	0	0	0	0	0	0
Inventory	1	1	1	1	0	1	1	0
Perception	1	1	1	0	1	1	0	0
Work-sharing	1	1	1	0	0	0	1	0
Approach	0	0	1	0	0	0	0	0

Factors were randomly assigned to the experimental units under the constraint of not assigning a treatment more than once to each group.

4. PRELIMINARY RESULTS

Experiments were conducted between March and May of 2011. No major incidents happened but for some eventual mistakes committed by the students when following the working procedures. These random errors were recorded as an error rate for each experiment. No significant effect from this error rate in throughput was found.

Data was collected from the software applications, videos and enquiries provided to the students. A preliminary analysis of the data recorded by the applications is now presented.

Applications records provided with lists of events occurred in the system. They spanned entries of lots in the system, exits from WS1, processed items in WS2 and exits in WS3. Thus it was possible to build a basic list of events happened in WS1, WS2 and the system as a whole. Then it was used to plot a graph of buffer contents and to calculate average residence times in the same fashion as the results that can be obtained from simulation software. A demonstration of the conducted results analysis is provided below.

Figure 5 displays the plot of slates in WS1 as a function of time. It includes the contents of buffers WS1, GB and RB plus the slates that are been processed by operator 1. Figure 6 displays a plot of the total residence time in the system as a function of the number of lot exited from WS3. The two observed leaps in residence times correspond to lots that suffered of a delay in WS3 due to starvation.

Tables 7 to 9 summarize the results of throughput rates achieved under the different treatments in sessions two and three. A regression model was fitted by least squares for the output rates of WS1, WS2 and WS3 containing terms for experience effect (numbering the production runs from 1 to 6) and several technical aspects. It can be noticed that only the experience factor was significant on the overall throughput rate (Table 9). This result contrasts with the expected benefit from increased buffer sizes or work-sharing that was expected. Actually, it was WS2 the one expected to be the one most favoured by the higher inventory conditions. WS2 was the process bottleneck, so by disposing an infinite buffer before it, random starvation caused by WS1 was removed and thus throughput should have been improved. However, evidence does not support this argument. Table 8 shows a high p-value for the low inventory effect, indicating that no significant effect was found. Furthermore, the terms sign is positive, which contrasts with the expected effect. Table 10 presents the effect expected by means of the simulation model. It can be seen that lowering buffers capacity significantly reduces throughput when human resources are modelled in a mechanistic way. Further analysis of results might provide more information on the roots of the observed deviance.

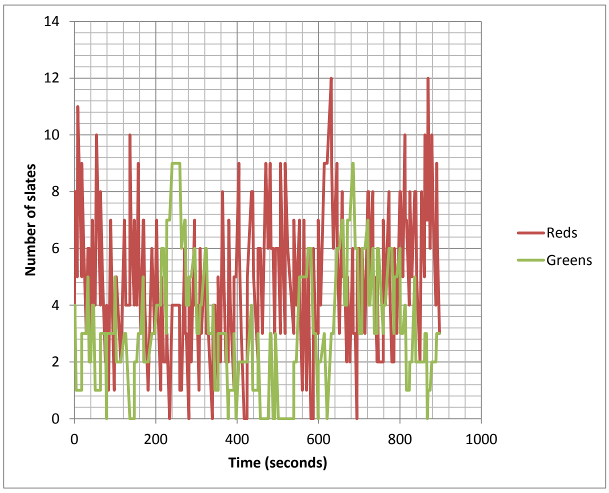


Figure 5: Slates contents in WS1.

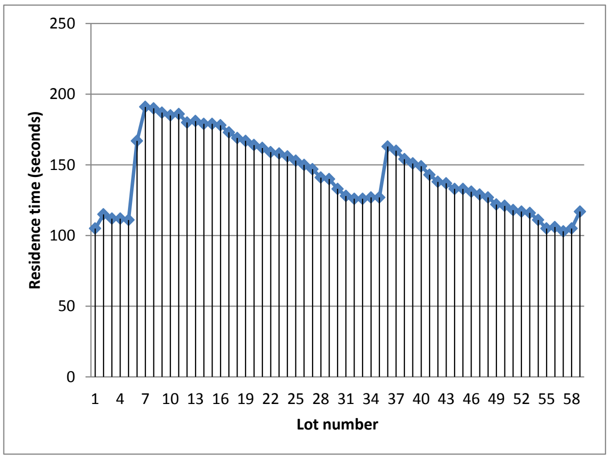


Figure 6: Total residence time of output lots in WS3.

Table 7: Regression model for WS1 output

Coefficient	Estimate	p-value
(Intercept)	0.135	0.000
Experience	0.005	0.004
Low Inventory	-0.024	0.004
Reduced Perception	-0.003	0.753
Work-sharing On	-0.017	0.056
Low Inventory & Reduced Perception	0.006	0.607
Reduced Perception & Work-sharing On	0.001	0.955
R Squared		0.3682
F Statistic		3.982
F test p-value		0.003137

Table 8: Regression model for WS2 output

Coefficient	Estimate	p-value
(Intercept)	0.124	0.000
Experience	0.004	0.003
Low Inventory	0.006	0.395
Reduced Perception	0.003	0.637
Work-sharing On	-0.001	0.937
Low Inventory & Reduced Perception	0.001	0.940
Reduced Perception & Work-sharing On	0.005	0.626
R Squared		0.4312
F Statistic		5.179
F test p-value		4.823E-4

Table 9: Regression model for WS3 output

Coefficient	Estimate	p-value
(Intercept)	0.042	0.000
Experience	0.002	0.002
Low Inventory	-0.003	0.423
Reduced Perception	-0.001	0.855
Work-sharing On	-0.001	0.799
Low Inventory & Reduced Perception	0.003	0.550
Reduced Perception & Work-sharing On	-0.001	0.834
R Squared		0.3039
F Statistic		2.983
F test p-value		0.01642

Table 10: Simulation results for inventory effect on WS2 and Z-test for differences in means.

WS2 Simulation (230 runs)		
Setting	**Mean**	**Std. Deviation**
Low inventory	31.44	1.18
High inventory	31.00	1.29
Z statistic		0.3039
p-value		2.983

5. CONCLUDING REMARKS

An experimental manufacturing system has been designed and built in the Industrial Engineering laboratory of the Escola Politecnica Superior de Ferrol. Sources of process variability other than those originated from human resources have been set up, monitored and kept under control. Thus, controlled variability is then characterized by means of a discrete events simulation model. A redundant data acquisition system has been implemented so that system events are traced and stored in a relational database in a computer simulator-like fashion. Real system production runs statistics are then compared with virtual model ones. Deviations in results are due to effects of human variation. Human performance models can be validated by introducing them in the simulation model and testing whether they actually improve the model prediction capability.

The system can also be applied for training in both simulation and process improvement tools. It provides a controlled environment in which the effect of factors of interest can be studied in depth and isolated from other factors. Data can be collected in large samples hard to obtain in many businesses processes. Model validation can also be performed in detail, directly comparing statistics from the real process with those from the virtual simulator. A major strength of this system is that subjects can take part as both operators and analysts, thus acquiring the two different points of view.

A twofold objective experiment has been conducted with cooperation from Industrial Engineering students of the University of A Coruna. A process inspired by a roofing slates manufacturing company was designed and installed in a laboratory setting. A joint research and educational activity was carried out aiming at testing the effect of ergonomics and organizational factors in manufacturing as well as a practical teaching in discrete events simulation. The students were organized in eight teams. Three initial sessions were run in which they had to work as process operators. Data was recorded and provided to the students once the initial sessions were ended. Then they had to simulate the process and to optimize certain proposed parameters. A final session was run in which the groups implemented their proposals and their results were compared and rewarded in a competitive fashion.

Some preliminary results have been obtained testing the effect on throughput of the studied factors. These factors span individual differences among groups, experience, buffers capacity, work-sharing, process state perception, ergonomic conditions and approach to either quality or quantity. Significant effects have been showed for the inter-groups variation, experience and ergonomic conditions. This is consistent with most of operations research literature on the effects of learning and either individual or group differences. No significant effects from changes in buffers capacity, work-sharing, process state perception and approach could be proved. This result contrasts with that obtained from a simulation model of the process in which human resources were introduced in a mechanistic way. Buffer capacity increase and work-sharing were expected to provide a significant increase in throughput. Although several limitations have been identified when extending these results to real manufacturing environments, they are consistent with the findings by Schultz et al. (1999, 2003). Human behaviour effects seem to be counteracting the expected benefits of increasing buffer capacities and enabling work-sharing. Further research is needed for assessing the validity of these findings and to deepen in the explanation of the causes.

REFERENCES

Baines T.S., Kay J.M., 2002. Human performance modelling as an aid in the process of manufacturing system design: A pilot study. *International Journal of Production Research,* 40(10), 2321-2334.

Baines, T., Mason, S., Siebers, P., Ladbrook, J., 2004. Humans: the missing link in manufacturing simulation? *Simulation Modelling Practice and Theory*, 12, 515–526.

Bendoly, E., Prietula, M., 2008. In “the zone”. The role of evolving skill and transitional workload on motivation and realized performance in operational tasks. *International Journal of Operations & Production Management,* 28 (12), 1130-1152.

Bendoly, E., Croson, R., Goncalves, P., Schultz, K., 2010. Bodies of Knowledge for Research in Behavioral Operations. *Production and Operations Management*, 19 (4), 434–452.

Bley, H., Reinhart, G., Seliger, G., Bernardi, M., Korne, T., 2004. Appropriate Human Involvement in Assembly and Disassembly. *CIRP Annals - Manufacturing Technology*, 53 (2), 487–509.

Elkosantini, S. and Gien, D.(2009) 'Integration of human behavioural aspects in a dynamic model for a manufacturing system', International Journal of Production Research, 47: 10, 2601 — 2623

Neumann W.P., Winkel J., Medbo L., Magneberg R., Mathiassen S.E., 2006. Production system design elements influencing productivity and ergonomics: A case study of parallel and serial flow strategies. *International Journal of Operations & Production Managemen,* 26(8), 904-923.

Neumann W.P., Medbo P, 2009. Integrating human factors into discrete event simulations of parallel flow strategies. *Production Planning & Control,* 20 (1), 3-16.

R Development Core Team, 2005. R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria.

Rego Monteil, N., del Rio Vilas, D., Crespo Pereira, D., Rios Prado, R., 2010. A Simulation-Based Ergonomic Evaluation for the Operational Improvement of the Slate Splitters Work, *Proceedings of The 22nd European Modeling & Simulation Symposium*, pp. 191-200. Fez, Morocco.

Riedel, R.; Mueller, E.; von der Weth, R.; Pflugradt, N.; , "Integrating human behaviour into factory simulation- a feasibility study," Industrial Engineering and Engineering Management, 2009. IEEM 2009. IEEE International Conference on , vol., no., pp.2089-2093, 8-11 Dec. 2009

del Rio Vilas, D., Crespo Pereira, D., Crespo Mariño, J.L., Garcia del Valle, A., 2009. Modelling and Simulation of a Natural Roofing Slates Manufacturing Plant. *Proceedings of The International Workshop on Modelling and Applied Simulation*, pp. 232-239. September 23-25, Puerto de la Cruz (Tenerife, Spain).

Powell, S.G., Schultz, K. L., 2004. Throughput in Serial Lines with State-Dependent Behavior. *Management Science,* 50 (8), 1095–1105.

Schonberger, R.J., 1982. *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity*. The Free Press, New York.

Schultz, K.L., Juran, D.C., Boudreau, J.W., McClain, J.O., Thomas, L.J., 1998. Modeling and Worker Motivation in JIT Production Systems. *Management Science*, 44 (12), Part 1 of 2, 1595-1607.

Schultz, K.L., Juran, D.C., Boudreau, J.W., 1999. The Effects of Low Inventory on the Development of Productivity Norms. *Management Science*, 45 (12), 1664-1678.

Schultz, K.L., McClain, J.O., Thomas, L.J., 2003. Overcoming the dark side of worker flexibility. *Journal of Operations Management,* 21, 81–92.

Schultz, K.L., Schoenherr, T., Nembhard, D., 2010. An Example and a Proposal Concerning the Correlation of Worker Processing Times in Parallel Tasks. *Management Science,* 56 (1), 176–191.

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