Simulation and Model Sensitivity Analisys of a Wind Turbine Tower Manufacturing Plant

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Keywords: Wind Turbine, Manufacturing, Industrial Process.

Abstract: A modelling method for a complex wind turbine tower manufacturing plant is proposed, through the specification of the major assumptions in the model. Using this methodology a DES model was developed, and a sensitivity analysis to some of the main process variables accounted for in the model is presented. From this study several versions of the model were developed, and their results are compared against real data from a manufacturing company.

1 INTRODUCTION

With early applications for water pumping and milling, the use of wind energy dates back to the 2nd century B.C. (Brito, 2014) with the first wind mills. In recent years, having developed greatly trough the 70's as consequence of the oil crisis (Hemami, 2012), wind energy plays an important role in today's society. In Portugal, according to REN (Redes Energéticas Nacionais, 2013), at the end of 2012 almost 23% of the connected power was obtained using wind. Nowadays, most wind towers in use can be described by the four major components: tower, rotor (hub and three blades), nacelle and foundation (Hemami, 2012). In this paper the manufacturing process of a tubular metallic tower is considered and modelled using DES.

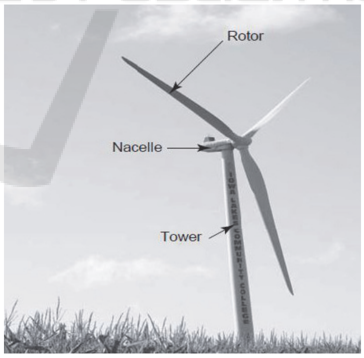

Figure 1.1: Typical modern wind tower with tubular metallic tower (Hemami, 2012).

A model is defined as the representation of a system with the purpose of studying it. Only aspects that influence the problem in study must be considered and then represented in the model. By definition the model is a simplification of the real system (Banks, et al., Fourth Edition).

It is possible to classify computational simulation according to three categories: Monte Carlo Simulation (MCS), Continuous Simulation (CS) and Discrete Events Simulation (DES). MCS uses generation of random numbers to simulate, without considering time explicitly as a variable. This method of simulation is defined by Law and Kelton (Law & Kelton, 2000) as being "a scheme using random numbers that are used to solve deterministic or stochastic problems where time plays no role". CS models use a set of equations in representation of

2 MODELLING

2.1 Simulation Methods

According to McHaney (McHaney, 2009), computer simulation can be broadly defined as:

"Use of a computer to imitate operations of a real world process or facility according to appropriately developed assumptions taking the form of logical, statistical, or mathematical relationships which are developed into a model."

Tomé P., Teixeira E., Assunção F., Marques L., C.P. Reis J. and M.C. Sousa J..
Simulation and Model Sensitivity Analisys of a Wind Turbine Tower Manufacturing Plant.
DOI: 10.5220/0005040807250732
In *Proceedings of the 4th International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2014), pages 725-732
ISBN: 978-989-758-038-3

a system evolution trough time. DES is characterized by blocks of time when nothing happens until an event changes the state of the system.

For this study, DES methodology is considered. The definition of important concepts as system, system state, entity, attributes, events and others can be found for instance in references (Banks, et al., Fourth Edition) and (Altiok and Melamed, 2007).

2.2 Case Study

The desired model is required to simulate to a certain degree of accuracy the resource allocation and production output of part of a Portuguese wind turbine tower manufacturer, in order to help the company evaluating the effect of altering key variables in production time.

According to the company, a tower is produced from smaller elements (in Portuguese named: *virolas*) welded to each other in order to become a section of a tower (in Portuguese named: *tramos*). The sections are then assembled on sight for obtaining the complete tower. A simplification of the process flow is given in figure 2.2.

Figure 2.1.a: *Virolas*.

Figure 2.1.b: *Tramos*.

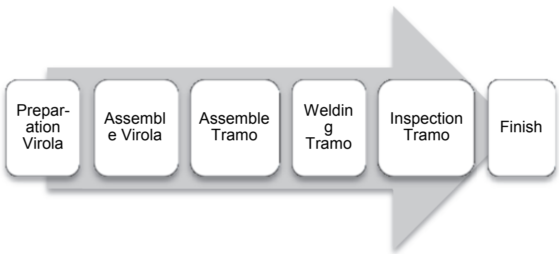

Figure 2.2: Production flow.

The considered entities (Virolas) are assumed to have an unlimited stock. Therefore the operations of "Preparation" and "Assemble Virola" do not interfere with the production and for this reason they are not modelled.

A tower built from 34 Virola elements welded to form 5 Tramos sections, according to figure 2.3 is considered.

The production of a subsection consists of the operations of transportation of the elements to the production line, welding, inspection, assembling of accessories and other operations. For each production line, depending on the section in production, around 65 to 90 different operations can be executed in order to manufacture that section.

Figure 2.3: Sections of the considered tower (TEGOPI).

As an example, the simplified flow diagram for the lower section S5 is presented in figure 2.4. The simplification is due to some operations being grouped, as is the case of "welding" that represents a sequence of six different welding operations.

Since each process requires different machine and worker resources, in order to be able to evaluate the impact of changing the availability of any of them in the model, the modelled system features:

- 10 production lines
- 20 vehicles
- 26 different resources
- 12 worker profiles
- Around 500 operations

2.3 Model Assumptions

With the purpose of modelling the studied system in an objective way, a set of assumptions was defined, such as:

i. The production orders are to be specified for the sections (Tramos)

ii. The created entities are transported to the production line by vehicles and workers simultaneously

iii. The vehicles mentioned in ii travel in specific networks and have a limit for the maximum transporting weight

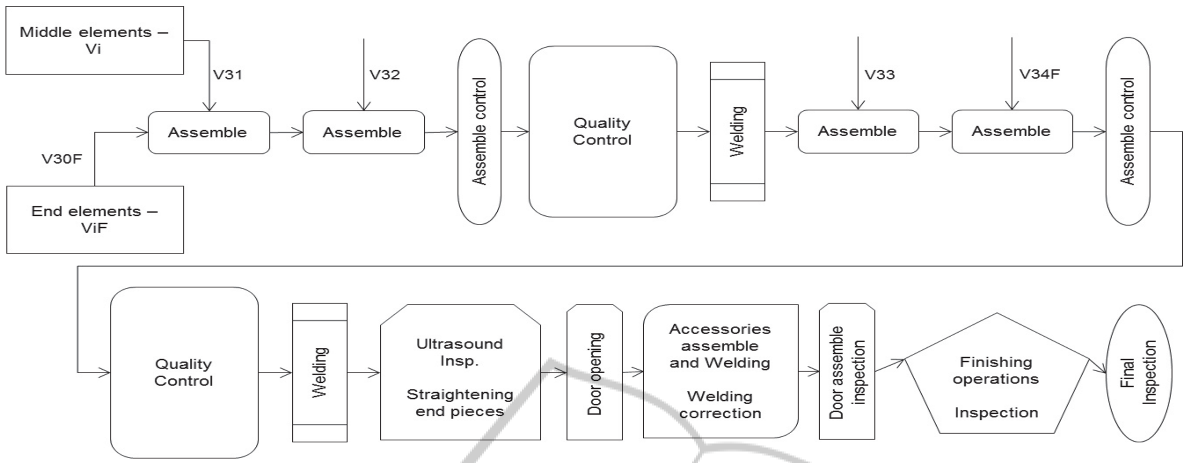

Figure 2.4: Simplified flowchart of the manufacturing process of section S5.

iv. All vehicles are "driven" by two workers, where the profile of the worker is depending on the entity type to transport.
v. At the production line the entities are processed according to the array of operations specified by the company
vi. Whenever a shift is interrupted or finished, the workers assigned to the running operations are released
vii. At the beginning of a shift where pending operations exist, those are resumed according to the priority associated to the respective entities.

In addition, two specific production lines are assigned to the production of each specific section due to weight constraints of the vehicles.

Production orders are given for the sections by specifying a start date and a destination production line. As soon as one element reaches the assembly stand of one production line, the next element of the production sequence is created and sent to this same production line. Initial element priorities can be specified for each entity and destination production lines.

If an order for the production of a section is given and the destination production line is busy, the model will create the entity, but this entity will not be allowed to leave the stock area until the destination line finishes the work in progress. Then becoming available to processes the new ordered section.

The model takes transportation times according to the distances from stock to production line locations into consideration. After completing the transportation tasks, the vehicles stay idle at the unload station. For accepting a transportation request a condition is evaluated. This condition specifies that the chosen vehicle is one of the available ones and has a load capacity that is enough to carry the element, but with the lowest possible carrying capacity.

All operations are performed by at least one worker sometimes using resources to perform the task.

Having had access to the average times of the different operations only but knowing that this times are not constant, a time distribution is used to model this behaviour. According to reference (Altiok & Melamed, 2007), a triangular distribution can be used when the actual time distribution is unknown but it is reasonable to assume that minimum (a) and maximum (b) possible values exist and that the most likely value (c) is inside this interval. Triangular distributions are defined by the following function:

$$f_X(x) = \begin{cases} \dfrac{2(x-a)}{(b-a)(c-a)}, & for\ a \le x \le c \\ \dfrac{2(b-x)}{(b-a)(b-c)}, & for\ c \le x \le b \\ 0, & otherwise \end{cases} \tag{1}$$

In the model the average value provided by the company is considered to be the most likely value (c). The minimum and maximum values (a and b) are obtained applying a percentage deviation around c. The model considers 5% deviation around c, but it is possible to change this rule easily by using the spread sheets attached to the model.

Multiple profiles of workers are defined (12 in total) according to the company's specifications. These profiles are not flexible to perform a task from another profile. The same applies for resources. This implies that an interrupted operation can only be resumed when the needed worker profile(s) and resource(s) are available to attend this task. Workers and resources "capacities", costs and reliability logic (the last only for resources) are able to be feed easily and changed into the model through the attached spread sheets. For the later purpose of model validation reliability logic is not considered since it is not mentioned in the supplied data.

3 RESULTS ANASLYSIS

According to Kelton (Kelton, Smith, Sturrock, 2013), only for the simplest models one is able to prove categorically the aspects of correct modelling. Therefore, the model should be tested in a way that is possible to verify that it behaves in the desired manner. First the model sensitivity to changing key variables is tested and analysed. Latter, data provided from the company is used to evaluate model performance. Multiple versions of the model are used to verify this point.

3.1 Sensitivity Analysis

Since transportation of elements from the stock location to the production line takes a considerable amount of time, figure 3.1 shows the production time using calculated distance (Model*1) or an smaller average distance (Model*2) for the production of section S5 in production line 8.

As expected, the net time needed for the production of this section decreases when average distances are considered. A decrease in occupation times of both workers (PF1 and PF8) and vehicles can be observed in figure 3.2 with a greater level of detail.

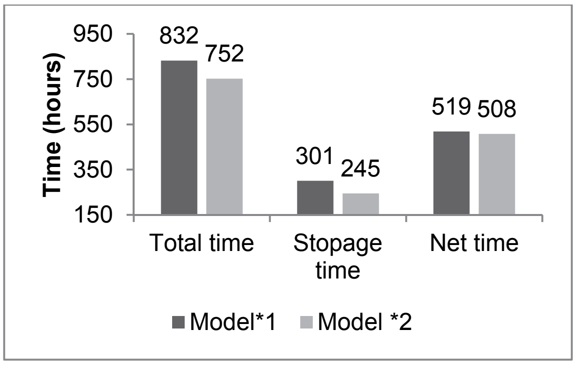

Figure 3.1: Production times: section S5 figuin line 8.

In fact, when the complete model is considered and production orders that lead to the manufacture of 4 towers are given, Model*2 needs about 3 days less of labour for finishing the production.

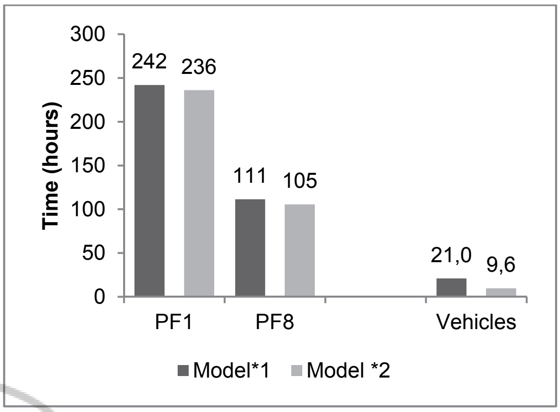

Figure 3.2: Resources occupation: section S5 in line 8.

The order in which operations are executed is related to the priority given to the entities (Virola) in processing. Once that the number of resources is limited, situations can occur where not enough resources are available to attend to all requested operations. Therefore, the priority assigned to entities plays an import role in the system and by changing this parameter model results should be affected. According to the company TEGOPI - Industria Metalomecânica, S.A., Portugal, the priority is defined to be highest for entities of section S5 followed by the entities of sections S1, S4, S3 and therefore, S2 entities were given the lowest priorities of the set. This configuration is used in both Model*1 and Model*2.

A new set of priorities was defined for Model*3 by keeping the relative priority of the different sections but increasing priority of the sections that will form the two first towers. This way assuring that priority is given to an older production order and by doing so a better approximation to the real system should be achieved. A summary of due dates obtained with the models considered up to this point can be observed in table 3.1.

Table 3.1: Due dates summary.

	Due date		
	Model*1	Model*2	Model*3
4th tower	8-May-13	3-May-13	30-Apr-13

In the construction of the model, special attention was placed into the allocation of workers to operations. Since specific profiles of workers are used to perform operations on the job-shop using resources of some kind, varying the available number of workers and their profiles should have a major effect on the delivery dates. This effect can be observed through analysis of the results obtained with Model*4. Model*4 is built from Model*3 but setting an unlimited number of both workers and resources.

Table 3.2: Limited VS Unlimited resources.

	Due date	
	Model*3	Model*4
1st tower	28-Feb-13	15-Feb-13
2nd tower	4-Apr-13	25-Feb-13
3rd tower	10-Apr-13	21-Mar-13
4th tower	30-Apr-13	26-Mar-13

As expected, the model reacted to the increase of resources by reducing significantly the delivery times. Note that for obtaining the results above the number of workers used is much higher than the ones scheduled by the company. Figure 3.3 and figure 3.4 show the comparison of used resources.

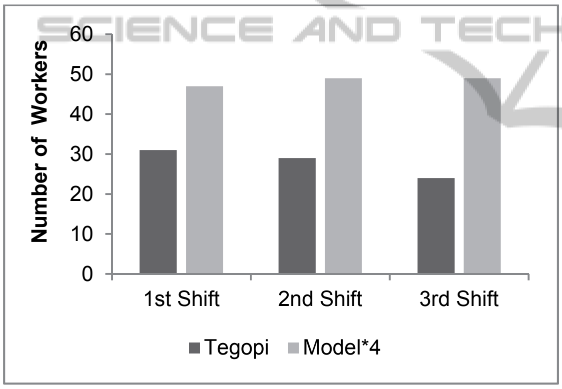

Figure 3.3: Workforce: TEGOPI VS Model*4.

3.2 Model Validation

Validation of the model is achieved by comparing delivery times of the different scenarios with data provided from the company.

3.2.1 Single Production Line

With knowledge of the average processing times of each operation to be performed in each section, it is possible to obtain an estimated average time for the total delivery time of each section. For this scenario unlimited resources were considered so that delays resulting from lack of resources do not occur.

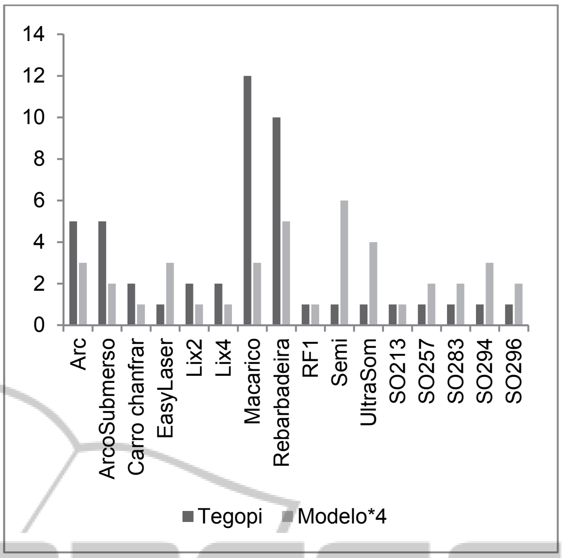

Figure 3.4: Resources TEGOPI VS Model*4.

Figure 3.5 to figure 3.7 show the occupation of the resources to manufacture section 5S for the cases: Validation scenario and Model*2. Model*2 is chosen because it considers average distances from stock to production, thus better matching the available data for validation.

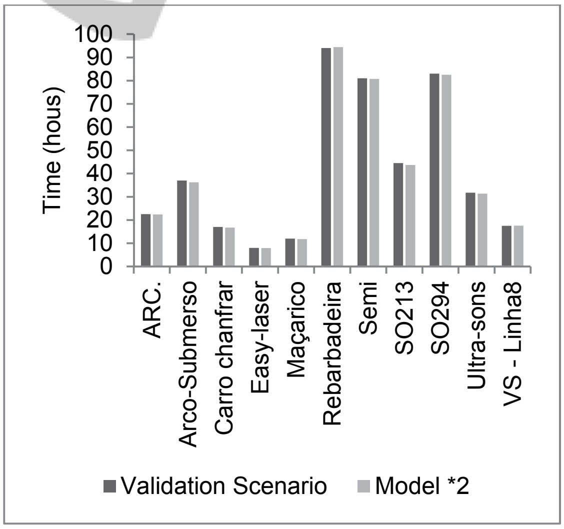

Figure 3.5: Machine occupation: section S5.

Deviations between 0.2% and 2.1% when compared with the validation data were obtained for machine occupation. Workers utilization varies up to 4.8%.

Regarding transportation times there is a 15.2% difference between the validation data and Model*2. In case Model*1 was considered, around 21 hours of total transportation time would be needed.

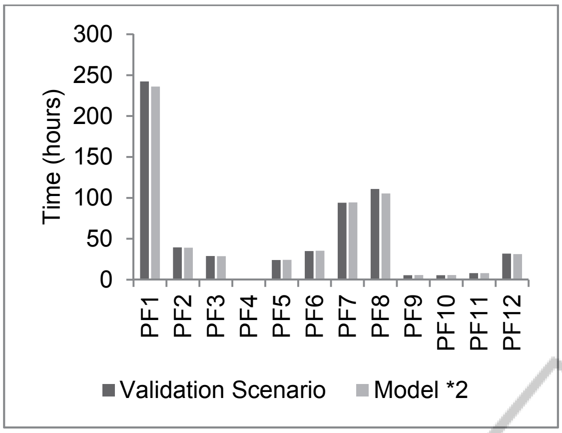

Figure 3.6: Workers occupation: Section S5.

Figure 3.7: Vehicles occupation: section S5.

Figure 3.8 compares the net production time used.

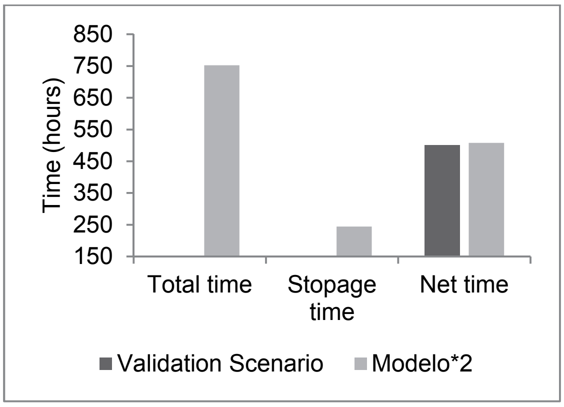

Figure 3.8: Production time: section S5.

3.2.2 Validation Scenario

Having already verified model sensibility to key parameters, the considered models can now be compared to the expected due dates from the validation data.

Although the model results may seem to be poor some considerations must be taken into account:

- According to the supplied data there are shifts where worker profiles are not available (e.g.: PF6 is not available on the third shift).

  Meanwhile, on the data for validation this situation appears not to occur since there is no indication of delayed operations as result of missing workers.
- In simulation it often occurs, that after the end of a shift the next shift does not have enough resources to resume all interrupted operations. Priority operations are resumed first. This can lead to delay due to lack of resources in low priority operations.
- Model does not consider workers to be flexible.

Take for instance an operation that uses the worker profile above (PF6) and that is interrupted in the end of the 2nd shift. This operation can only be resumed after one shift of interruption, affecting the production time due to this delay.

3.2.3 Unlimited Resources

A version of the model with unlimited resources and average paths (Model*4) is used. This allows the model to get closer to the data for validation, according to table 3.4.

For the first and second towers results are matching the expected since the production lines start free and times are not affected by delay. For the next towers delay occurs since the production lines are occupied when the production order reaches the system.

Table 3.3: Due dates: Multiple scenarios.

	Validation Data		Due Date		
	Production Order	Due Date	Model*1	Model*2	Model*3
1st tower	11-Jan-13	13-Feb-13	11-Mar-13	26-Feb-13	28-Feb-13
2nd tower	18-Jan-13	22-Feb-13	22-Mar-13	21-Mar-13	4-Apr-13
3rd tower	23-Jan-13	15-Mar-13	29-Apr-13	1-May-13	10-Apr-13
4th tower	28-Jan-13	19-Mar-13	8-May-13	3-May-13	30-Apr-13

Table 3.4: Due dates: Model*4.

	Validation Data		Due date Model*4
	Production Order	Due Date	
1st tower	11-Jan-13	13-Feb-13	15-Feb-13
2nd tower	18-Jan-13	22-Feb-13	25-Feb-13
3rd tower	23-Jan-13	15-Mar-13	21-Mar-13
4th tower	28-Jan-13	19-Mar-13	26-Mar-13

Table 3.5: Due dates tower 3 and 4: Model*4.

	Validation Data		Due date Model*4
	Production Order	Due Date	
3rd tower	23-Jan-13	26-Feb-13	27-Feb-13
4th tower	28-Jan-13	4-Mar-13	5-Mar-13

To eliminate this effect, a scenario for the production of towers three and four only was simulated. Results in table 3.5 show that the due dates in this situation are inside the acceptable limits for the model.

In order to achieve these results, Model*4 used 145 workers. The company actually scheduled 84 workers. A situation in which the number of workers used is higher than the number scheduled is verified.

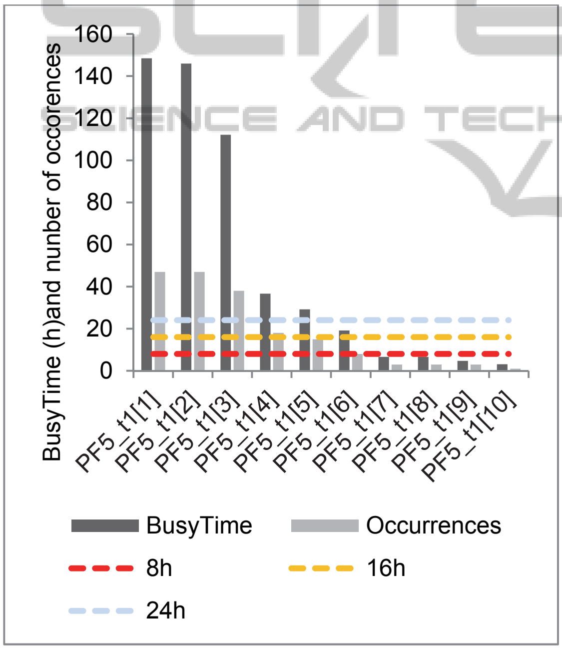

Figure 3.9: PF5 1st shift usage: Model*4.

The number of workers PF5 of the 1st shift (PF5_t1) is chosen because it represents the bigger deviation.

Four workers are scheduled by the company and ten were used by Model*4. Figure 3.9 shows detailed statistics regarding the workers of PF5_t1 used by Model*4. Hence profiles PF5_t1[7] to PF5_t1[10] are used for less than a eight hours shift, results appear to show that the model lacks some logic for task selection preventing that, for example, a task with more than eight hours duration starts close to the end of a shift.

In a situation when more workers are available, a larger number of machine resources is used according to figure 3.10.

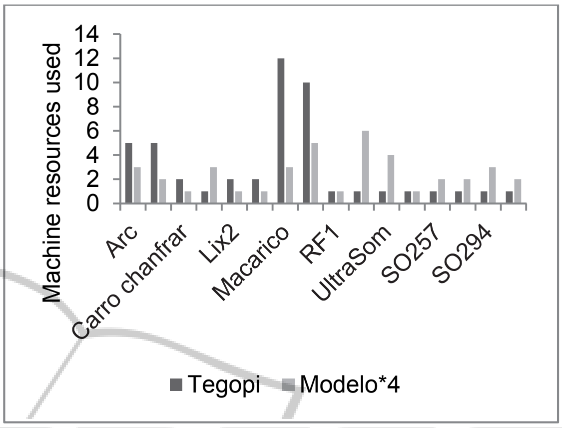

Figure 3.10: Allocated machines: Model*4.

3.2.4 Tuning of Model Assumptions

In this version of the model another approach is used, using the knowledge that for completing the scheduled production of the four towers the company spent three months. The model will be used to achieve this delivery time using a number of workers similar to the one scheduled by the company.

Model*4 is used as the starting point and then, the number of workers is limited based on the previous usage time. Workers with less than 10 hours of use are discarded for the next run. Using the previous example of PF5_t1, in Model*5 the number of workers of this profile is limited to 6. This way Model*5 uses 96 workers but still more machines than the number scheduled by the company. Now limiting the number of machines according to specification (Model*6) and then reducing five more workers (Model*6.1) the model has provided the following results.

Table 3.6: Due dates: Model*6 and Model*6.1.

	Due date		
	Model*5	Model*6	Model*6.1
1st tower	15-Feb-13	19-Feb-13	21-Feb-13
2nd tower	25-Feb-13	4-Mar-13	5-Mar-13
3rd tower	21-Mar-13	22-Mar-13	28-Mar-13
4th tower	26-Mar-13	5-Apr-13	9-Apr-13

With delivery time of approximately three months, Model*6.1 uses a total of 91 workers meaning 8.3% above the number of workers specified by the company. Although more workers are used in simulation, this value is according to the company's expectation for the model's performance without considering resource flexibility.

4 CONCLUSIONS

The proposed model allowed the analysis of the behaviour of the studied system. Although the model represents all the production process with a reasonable degree of detail, special emphasis was given to workers allocation to tasks. Nevertheless it is easy to change other parameters and test more scenarios.

Individual production lines were studied and analysed in greater detail by verifying worker and resources utilization and completion time to ensure they could be used for correct modelling of the overall plant.

It is possible to establish that transport traveling distance and priority logic have a significant influence in the response of the model. But more important, the model is very sensitive to changes in worker capacity and worker distribution by the several specialization profiles. This is due to the demand of at least one worker to execute each task from the productive process.

The model results agree with the data supplied by the company for the individual production lines. For the overall plant the results showed some discrepancies, but the sensitivity analysis allowed an identification of the most significant problems of the original model version. By redesigning some of the model assumptions and logic that were originally not part of the supplied data, it was possible to improve the model results to within 8.3% of error relative to the real data values. This result was considered as acceptable by the industrial partner under the assumptions that were considered.

ACKNOWLEDGEMENTS

This work was supported by FCT, through IDMEC, under LAETA Pest-OE/EME/LA0022 and partially supported by the project R046, IDMEC.

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