MODELLING AND SIMULATION OF A FISH PROCESSING FACTORY SHIP

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ABSTRACT

A fish processing factory ship is a large vessel with on-board facilities for the immediately processing and freezing of caught fish. This is a paradigmatic case of changing environment due to the uncertainty in the quantity and quality of the catch, the importance of the human factor and the frequent adverse operation conditions. Decision making processes are especially difficult to set regarding either resource allocation or the mix of products. This paper presents a case study in a Spanish company with special attention to the sources of variability. An overall exploratory DES model of the plant together with a specific DHM simulation of the workers tasks are developed as a means to gain insight into the process. The process efficiency in different production scenarios, the organizational effects in the packing workstation and the ergonomic and operational assessment of the wrapping operations are studied.

Keywords: Modelling and Simulation, Discrete Event Simulation, Digital Human Modelling, Fish processing, Factory ship

1. INTRODUCTION

A factory ship is a large vessel with on-board facilities for processing and freezing caught fish. There are about 24,000 vessels of more than 100 tons in the world's factory fishing fleet (FAO Archives 2004). According to Eurostat, in terms of tonnage the Spanish fishing fleet is by far the largest (415,000 gross tonnes) of Europe. This fleet produces around 1,000,000t of fish per year (FAO Archives 2007). The Spanish fleet is composed of 11,000 ships, but only 400 trawlers, seiners and liners account for 50% of the global tonnage. These are the ships that fish out of the EU territorial waters (Ministerio de Medio Ambiente, Medio Rural y Marino 2011).

The Spanish company involved in this study has fifteen trawlers that operate in the Southwest and Southeast Atlantic Ocean fishing grounds. Some of these trawlers are multispecies and other are rather specialized in one species. The most complex type of trawler –the multispecies- has two or three parallel lines capable of producing between 25t and 40t of frozen fish per day.

The on-board fish processing lines involve several production workstations with both manual and automatic operations. The analysis of such a system implies to consider the process flow through several parallel lines with different inputs and outputs. In fact, there is a great variety of final products. The uncertainty due to the quantity and quality of the catch makes it difficult to take the optimal decision regarding either resource allocation or the mix of products. The mathematical analysis is then quite complex to conduct. Even more, unless a dynamic approach is adopted, some key factors are very difficult to estimate, such as the time-in-process of the final product. There is a direct relationship between this parameter and the quality of the frozen fish (Trucco et al.1982). As a consequence, a simulation based analysis in order to assess different production alternatives has been considered.

To our knowledge, the fish processing has been seldom analysed under an engineering production perspective. It is remarkable the network-based simulation of a processing facility in land made by Jonatansson and Randhawa (1986). Among the results from their model are statistics on utilization of machines and workers in the process, size of in-process inventory at different locations in the process, and throughput times.

On the other hand, the working conditions of the operator have been widely discussed. Several ergonomic and clinical studies have been carried out. A clear prevalence of shoulder and upper-limb disorders among the workers in eight different factories in the Kaohsiung port (Taiwan) is reported in Chiang et al. (Chiang et al. 1993). A L.E.S.T. analysis (Ergonomic Evaluation Method developed by the Institute of Labour Economics and Industrial Sociology of France) was conducted to characterize the risk in a fish processing plant in Ecuador (Torres and Rodríguez 2007). Regarding the assessment of on board workers, a study of Swedish fishers showed that they experience frequent musculoskeletal disorders (MSDs), according to the type of task, but also a special type of stress due to the natural ship instability (Törner et al. 1988). Another critical factor of these operators is the level of noise, which has been also studied for workers of a fishing trawler (Szczepański and Weclawic 1991).

The process on board is highly dependent on human operators (between 45 and 65 people spend several weeks working on board). Due to hard working conditions, another aim of the study was to characterise the ergonomic impact of some tasks by means of digital human modelling (DHM). Some studies have already applied this tool to the fishing sector (Zhang 2010, Álvarez-Casado et al. 2011). DHM has been used to jointly consider productivity and ergonomic measures for the workstation design in a very wide range of sectors, like in the food industry (Ben-Gal I and Bukchin 2002), in mining (Rego et al. 2010) and in the automobile industry (Fritzsche 2010).

A combined simulation approach has been adopted for the characterization and improvement of the process: (i) a global analysis of the production system by means of discrete event simulation and (ii) an ergonomic study of the individual tasks. The aim of this paper is to describe the case study and the proposed methodology for its analysis. Although this is an on-going project, some relevant preliminary results are also described.

2. PROCESS DESCRIPTION

In spite the processing process starts and depends on the previous fishing process, only the indoor activities will be explained for the sake of simplicity. The flow diagram of the fish processing is depicted in Figure 1. Initially, the captured fish on deck is introduced into the processing plant by means of a ramp connected to a hopper which feeds a distribution conveyor belt. A manual classification (Figure 2) conveys the fish to the filleting line –Product "Fillet"-. If it is too big or too small to go to this filleting line, it goes to the whole fish line –Product "HG product"-. If it is not able to be processed in time or it does not fit the requirements, it is returned to the sea -Discards-.

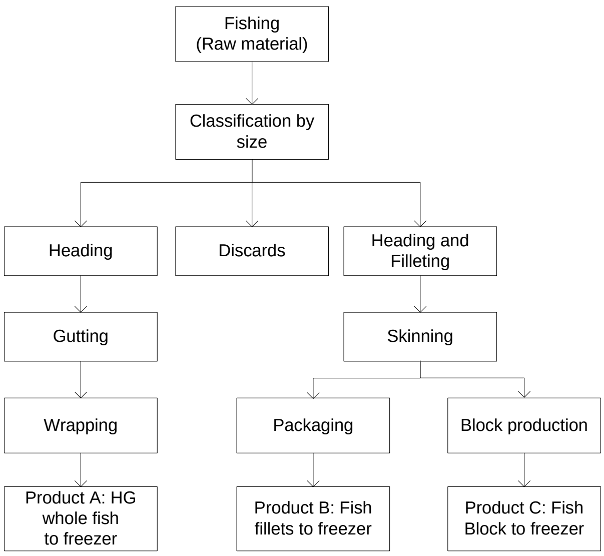


Figure 1. Flow diagram of the factory ship process

On the whole fish line, the fish undergo three sequential operations, named heading, gutting and wrapping. Heading and gutting operations are performed by two machines assisted each one by an operator. The fish without the head and the guts -around a 70 % of the weight of the fish- is washed in the second machine. It waits into an intermediate buffer to be wrapped by an operator. Finally, as showed in Figure 3, it is placed into a box with similar sized HG products (headed and gutted). The full box is ready to go to the freezing stage.

Figure 2. Manual Classification of the Fish.

Figure 3. Wrapped HG fish in a box.

If the fish has an adequate size, it is sent to the fillet lines. Three parallel workstations accomplish the heading, gutting, filleting and skinning of the fish. Each fish yields two fillets that directly go to the skinning, an operation that removes the skin from each fillet. The overall yield is estimated in 40% of the initial weight of the fish. The fillets are then conveyed to a common belt to be manually put into trays. This operation, the packing, consists on selecting similar sized fillets, trimming them if they still have rests on skin or bones, and place them forming several layers into a tray. A plastic sheet is placed between layers to avoid the adherence of fillets. The full box of fillets is then sent to the freezing stage.

Figure 4. Packed Fillets in a Tray

The fillets may be rejected from the packing operations. This eventually happens because they fail reaching the quality requirements or because the packing operators have not enough capacity to process them. In that case, they go to the so-called "fish-block" conformation. This third product is a block of fillets weighing 7.5kg and measuring 485mm x 255mm x 63mm, intended for further processing (breaded sticks, skewered fish, cooked dishes, etc.)

The overall variability exhibited in the process performance can be explained by several causes:

1. Product variability. An important difference between any processing plant and a factory ship is the greater uncertainty about what and when the raw material enters the process. This is due to the heterogeneous distribution of the fish along the sea and the irregular distribution of species and sizes. The different species morphology and size influence the availability to automatic filleting. This obliges the process to be flexible.
2. Process variability. Apart from the above mentioned influence of the species and sizes in the mix HG/fillets, there are other factors that link the product characteristics and the process parameters. First, when the fish waits too long before it is processed the Rigor Mortis makes too rigid to go through certain operations. In that case, a break down in filleting machines may occur. The second factor is the packaging capacity in the filleting line. When the volume of fillets coming from the skinning operation exceeds the manual packaging capacity, the fillets enter to the block production, a less-valued product.
3. Variability due to the resources. The human operations have a natural variability even if they are repetitive, due to factors like skill, mood, tiredness, hour of the day and experience.
4. Variability due to the environment. The ship rocking has a double consequence on the work development. On the one hand, the scales that can be used on board (able to compensate the movement of the ship) are unaffordable. This makes that they cannot be a part in the process as it is in land. As a consequence, weights on trays are estimated by operators and errors are introduced. On the other hand, it is a recognized stressing effect in the operators. Space restrictions often lead the operator to adapt to suboptimal workstation design. Besides, noise, vibration and humidity are factors that increase the risk of accidents.

3. SYSTEM MODELLING AND SIMULATION

Due to important logistic and economic constraints, visiting the actual plant while operating has not been possible. To overcome this disadvantage, process videos and production reports have been extensively analysed. Probability distributions for the sizes on the caught fish (table 1) and the cycle time for activities (operators and machines cycles) have been modelled. The parameters of the size of fish were obtained from the analysis of the production reports that provide data of final product categories packed and frozen during a set of working periods (usually three days). The general operation system was defined from the videos, layout information and interviews. Operators times were obtained from videos observation and machine cycle times were determined with the engineering department help.

Table 1. Fish Weight Categories (in grams)

Number of group	Range of weigh	Description
1	(0, 200]	Fit for whole line
2	(200, 500]	Fit for whole line or fillet line (second category)
3	(500, 800]	Fit for whole line or fillet line (second category)
4	(800,1500]	Fit for whole line
5	(1500, 4500]	Fit for whole line

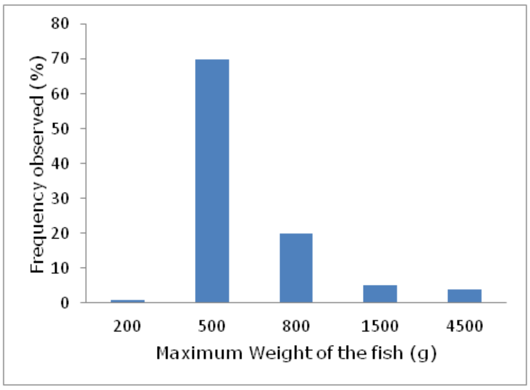


Figure 5. Expected Frequency of Each Fish Weight Category

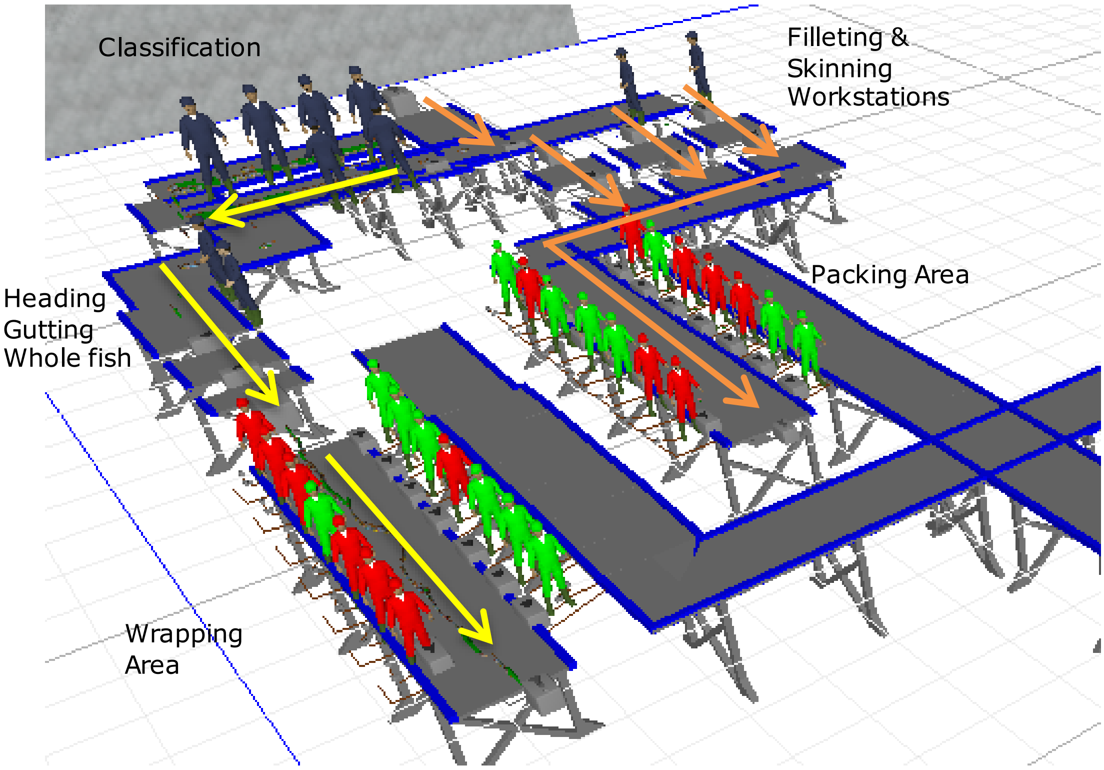


Figure 6. Simulation Model of the Processing Plant in the Factory Ship

The model was developed using SIMIO, an object-based 3D modelling environment. In the simulation model the fish are modelled as entities. The machines and operators are modelled as resources. However, the parameter unit varies depending on the specific operation (fish, lot or fillet).

- Fish. Standard unit from the initial source.
- Lot. During the classification the operator picks up several elements of fish at once –a lot-. The number of fish that compose a lot varies from one to four, according to two empirical distribution functions (to HG process, to fillet process). After the classification, the units are considered individually again.
- Fillet. In the filleting machines, entities modelled as fishes are destroyed after the process time, and two new entities are created as fish fillets.

Wrapping and packing operations imply an individual processing of the product (select, wrap or place) and a common processing as a box or tray (transport). The number of elements that form a box (for HG product) or a tray (for fillets) depends on their size. This has been considered an important factor, because the number of units per container influences the time-in-process of the products, the utilization of the operators and the global time spent in transport to the freezer.

Although a fish size distribution has been defined (Figure 5) this does not mean that all the group 2 and 3 sized fish are sent to the fillets line and the rest of the fish are sent to the whole fish line. A preliminary study of the maximum capacity of the lines regarding the fish supply and the mix of products has been done in order to evaluate this key parameter for the global efficiency of the plant (Figure 7).

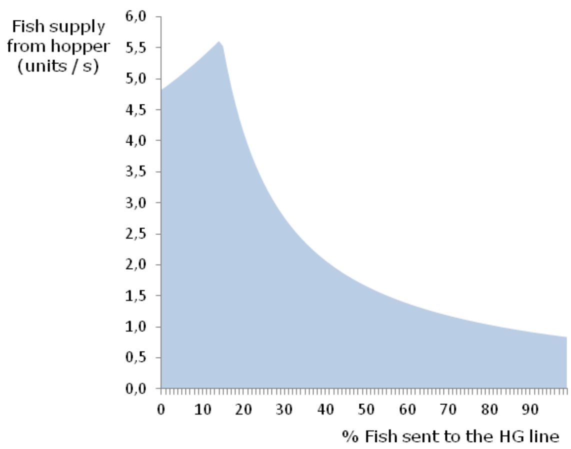


Figure 7. Maximum Supply Rate that can be Processed by the Filleting Machines depending on the Percentage of Product to Whole Fish (HG) Line.

As a result, it is clear that the maximum capacity of the plant occurs when the fish supply is 5.5 units per second and 15% of the supply is sent to the HG line. The normal operation of the factory ship should be close to this optimum working point. Three scenarios will be tested for three different mix of products (10%, 15% and 25% of fish supply sent to the HG line).

In order to define the state of the plant in each operation scenario, a set of performance indicators has to be defined. In this case, we will be accounting for variations in:

- Resource Utilization. Occupation of Operators and Machine compared with the total working time.
- Product Yield. All the fish supply that undergoes the process has four possible outputs: discards, frozen whole fish, frozen fillets and fish block. The production rates of discards and fish block are the variables related to the inefficiency of the system. As a consequence, a better product yield implies reducing them to the minimum.
- Time in process. The time in hours between its exit from the fish hopper and its freezing.
- Production rate. The rates in units per second of the main products of the plant.

Table 2. Summary Statistics of the Three Scenarios

State var.	Element	Scen. 1 (10% to HG)	Scen. 2 (15 % to HG)	Scen. 3 (25% to HG)
Resource utilization	Wrapping operators	48.1 %	58.2 %	78.6 %
	Packing operators	96.3 %	95.3 %	94.3 %
	Average HG machines	39.5 %	52.5 %	90.6 %
	Average fillet machines	48.9 %	47.9 %	44.2 %
Product yield	Fish supply to block	54.3 %	54.2 %	49.9 %
	Fish supply discarded	11.0 %	9.0 %	5.2 %
Time-in-process (h)	Average Time HG	0.12	0.11	0.11
	Average Time of fillets	0.13	0.13	0.13
Production rate	HG product (units/s)	0.22	0.27	0.37
	Fillets (units/s)	2.12	2.09	2.09

For a fish supply of 3 units/sec, Scenario 3 exhibits better resource utilization for the HG line, a better yield of the products (less discards and less fish supply sent to the lowest valued product) and a similar time in process. With a mix of 25% of fish supply sent to the HG lines and 75% to the filleting lines, the HG machines are close to saturation.

There is not a great difference between the resource utilization in the filleting lines. This can be explained because of the packing bottleneck that reduces the potential capacity of the line. This has been one of the reasons that suggest improving the ergonomics and productivity of the workstation.

4. WORKSTATION MODELLING AND SIMULATION

A supplementary analysis of the wrapping/packing organization task has been done. At present all the operators are placed around a common linear conveyor belt where the products coming from the automatic machines are processed (Figure 8). It has to be remembered that every box/tray has to be filled with similar sized HG fish/fillets (there are up to five categories). We have considered that the first product taken by the operator determines the size of the rest. As a result, in all the scenarios an effect of decrease on the utilization rate of the operators is produced as their distance from the source increases (Figure 9). This can be explained because the amount of products at the end of the line (when all the previous workers have chosen their products) is lower and the operator may eventually be blocked, waiting for a specific size to end a cycle.

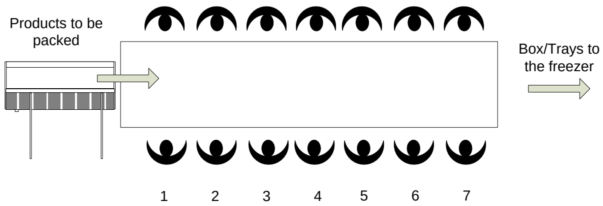


Figure 8. Present Organization of the Wrapping Operators (M1)

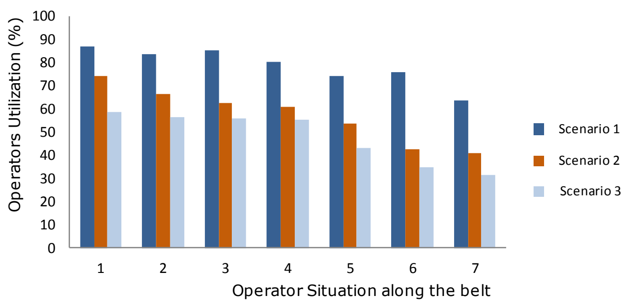


Figure 9. Utilization of the Wrapping Operators related to their Position along the Conveyor Belt

Accordingly, an alternative arrangement of the workers has been modelled. The idea was to divide the operators in two teams. This idea assumes that neither space restrictions nor technical problems hinder the product flow from being divided.

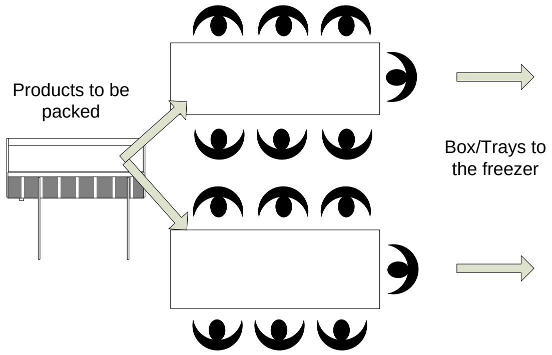


Figure 10. Alternative Distribution of the Wrapping Workstation (M2)

A design of experiments (DOE) approach with two factors –input rate and belt speed- has been considered to compare both models in terms of wrapping performance. The wrapping performance accounts for the proportion of fillets that are effectively processed by the operators and send to the freezing stage.

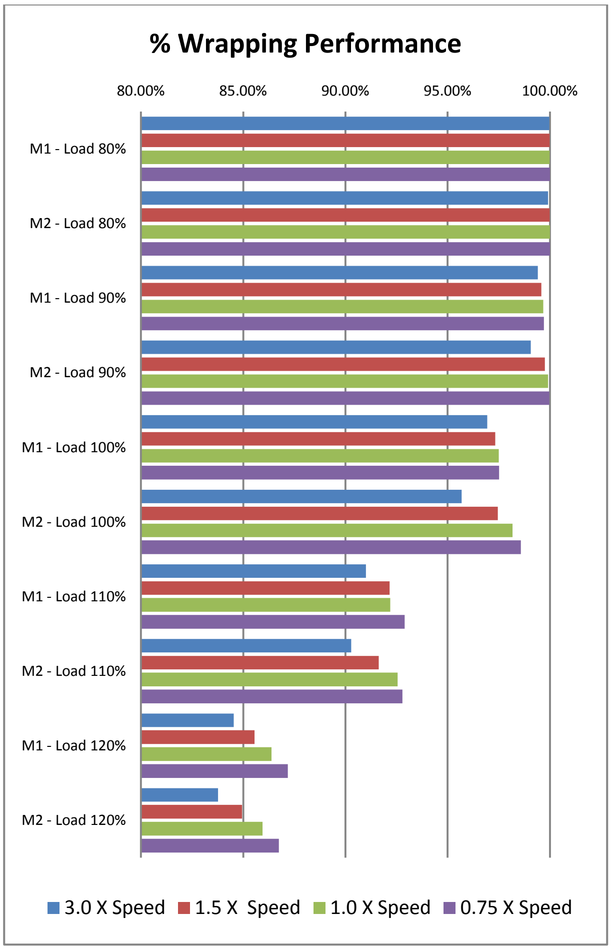


Figure 11. Wrapping Performance depending on the Operators Location along the Belt.

Results are shown in Figure 11. When the input rate is set at 100% and the belt speed is reduced, the M2 distribution achieves better results than the M1 one. For the rest of the cases, M1 behaves better than M2.

For its ergonomic evaluation, the wrapping activity will be decomposed in several components or subtasks. Each subtask is now described as follows:

1. Pick up. The operator bends his back to reach a fillet from the belt (see Figure 12.a.)
   A set of three reach areas have been modelled to cover the entire possible pick up movements.
2. Trimming. If needed, fillets are scissor cut to make them look better and to remove leftover bones (see Figure 12.b).
3. Place on the tray. The fillet is placed on the tray (see Figure 12.c).
4. Plastic sheet between layers. The layer is usually complete after 4, 5 or 6 fillets. A plastic roll is then unwind over the fillets layer. This roll can be seen in Figure 12.c.
5. Tray placed on freezer belt. The tray full of fillets weights around 8 kg. At that point the plastic sheet is cut and the tray is placed over an upper conveyor belt at workers' shoulder level (see Figure 12.d).

Figure 12. Samples of Postures during the Wrapping Operation –(a) Pick up; (b) Trimming; (c) Place Fillet; (d) Place Tray-.

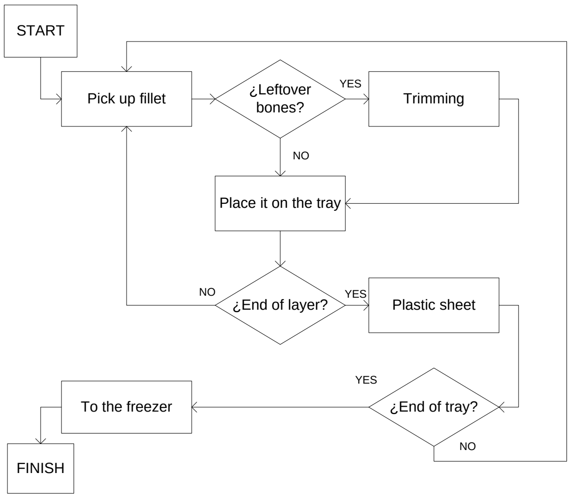
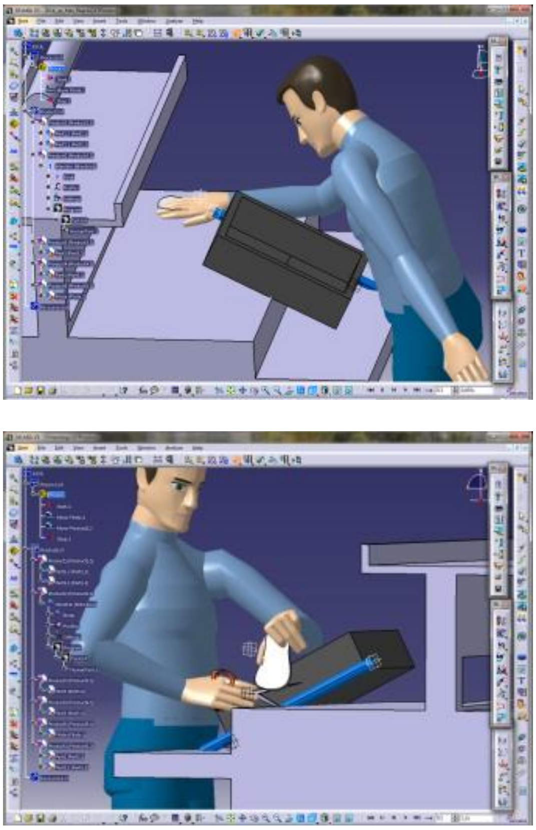


Figure 13. Flow Diagram of the Wrapping Operation

The above mentioned subtasks have been modelled in Delmia V5R20. Their analysis has been done according to the methodology presented in a previous work (Rego et al. 2011). The first stage implies modelling the operators, assuming they fit to the 50th percentile of the French population. The workstation and the tools employed have been modelled by using the geometrical information that the company provided.



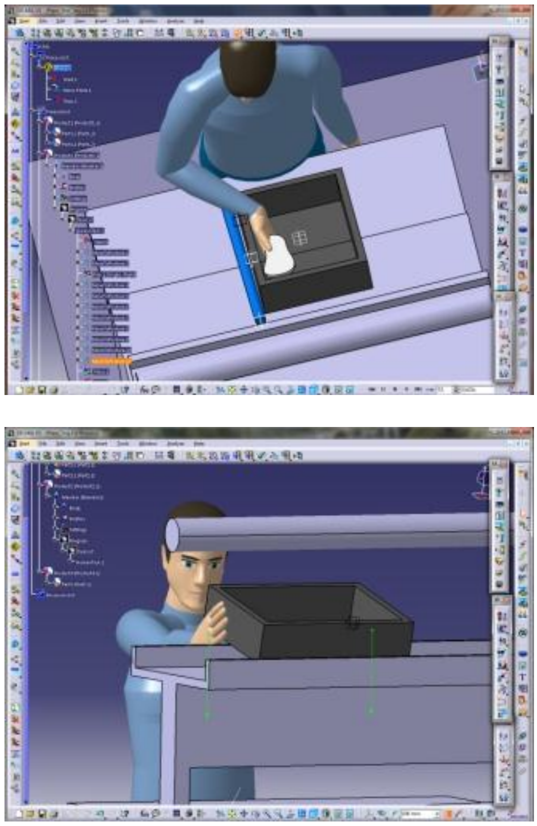


Figure 14. Modelled Postures of the Subtasks -(a) Pick up Max Reach; (b) Trimming; (c) Place fillet; (d) Place Tray.

The RULA score index has been chosen to report the ergonomic evaluation of each subtask. RULA is a well-known and widely used ergonomic assessment method (Cimino et al. 2008) and it is especially thought for the assessment of tasks that mainly imply the upper limbs. The final score is related to the risk of the posture, and goes from 1 (no risk at all) to 7 (urgent need of change to avoid injury). The L4/L5 compression limit has been also considered as an important indicator of the biomechanical risk associated to the adopted postures. The Spine Compression value is a complementary measure of risk of MSDs. According to NIOSH guidelines, compression force on the intervertebral disk above 3.4kN may eventually lead to injuries. Delmia V5R20 provides with both indicators to evaluate each posture of which an activity is made of.

The following charts represent the previous indicators for the different subtasks. As it can be noticed, in Figure 15, the RULA score reaches high levels of risk during the maximum reach pick up task and the place tray task. The L4/L5 compression limits (Figure 16) supports this result with a similar evolution. However, the 3.4 kN limit is never achieved. The rest of the subtasks –place fillet, plastic sheet and trimming operation- remain in relatively “safe” levels.

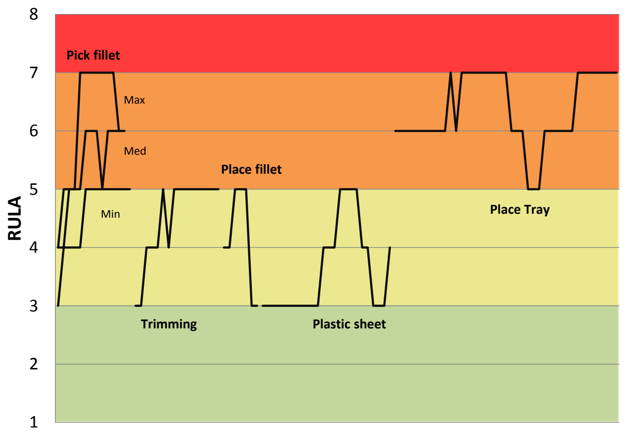


Figure 15. Postural risk of the modelled subtasks

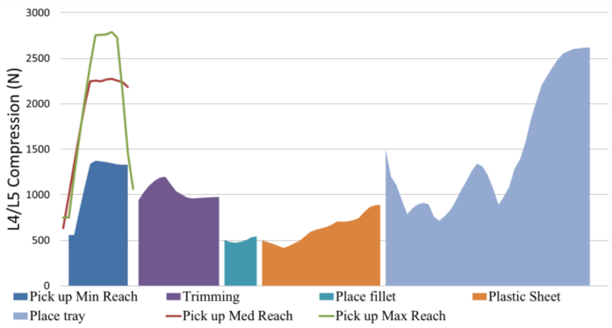


Figure 16. Compression Force on the Intervertebral Disc between L4 and L5 for the modelled Subtasks

Table 3. Summary of results for the wrapping operation

	RULA Score		L4/L5 Comp.	
	Avg	Max	Avg (N)	Max (N)
Pick up Min	4,75	6	1206,18	1375
Pick up Med	5,07	6	1912,71	2275
Pick up Max	6,15	7	2041,38	2789
Trimming	4,50	5	1034,94	1198
Place Fillet	4,14	5	502,43	544
Plastic Sheet	3,58	5	627,65	891
Place Tray	6,37	7	1473,87	2619

A complementary analysis can be done by performing a separately assessment of the different body segments. The RULA method correlates each segment range of movement with the risk of injury. In Figure 17 we present a rate of the average RULA score for each subtask related to the maximum score. In agreement with the literature (Chiang 1993, Törner 1988), there is a clear prevalence of upper limb risks. The forearm and wrists are the most likely parts of developing MSDs. Another remarkable result is that even though the trimming and the place fillet operation were not dangerous in terms of the global analysis, in this analysis they show the highest rates of risk in forearm and wrist.

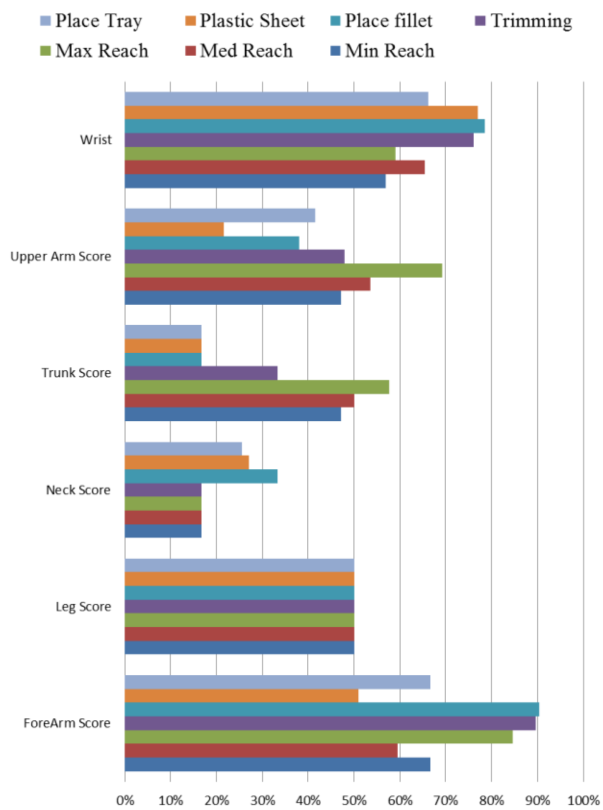


Figure 17. Body Segments Ergonomic Risk for each Subtask

5. VALIDATION AND RESULTS

During the modelling stage a continuous verification effort has been performed by comparing the model with the videos, production reports and the analysis of the real operation times. Validation of preliminary results has been done by a group of experienced workers from the company who found the results to be reasonable according to their experience. For the ergonomic model validation, we also took into account that the literature was in agreement with the main results. Finally, the following findings should be highlighted:

1. The product mix is a key parameter that strongly influences the production rate and the resources utilization. Due to the filleting machines limiting capacity, the point of maximum efficiency of the plant is set to a process input rate of 5.5 units per second and a product mix of 15% to HG lines and 85% fillets.
2. Although the process is oriented to the production of fillets, a more balanced mix between HG product and fillets benefits the product yield and the occupation rates when the input rate is set to 3 units per second.
3. The bottleneck operations are the wrapping operation in the fillet lines and the packing operations in the HG lines.
4. The organization of these workers (wrapping and packing) around a common belt has the effect of decreasing their utilization rate as they are placed

farther from the source. A higher specialisation (two different belts with fewer operators per belt) was tried as an alternative. Their wrapping performance is similar, although in almost all combinations of belt speed and input rate the original organization was slightly better. A 5.02% of fillets could not be processed in the first design, whereas a 5.14% in the second design went to the less valued sub-product (the fish-block).

5. A redesign of the wrapping operation and workplace seems convenient due to their central role in the whole process.
6. The ergonomic analysis of this task showed that placing the full tray of fillets on the upper belt and reaching the fillet from the maximum distance are the hardest tasks in terms of RULA score and L4/L5 compression. The use of smaller trays and an alternative location of the to-freezer-belt should be studied in order to reduce the impact of the "placing full tray task". A redesign of the workplace to reducing the reach distance would indeed decrease the need of back bending.
7. The analysis of the different body segments showed prevalence on wrist and forearm risk. The trimming operation is one of the most demanding in terms of wrist and forearm postures. A better scissor design, amongst other measures, should be proposed in order to reduce the probability of injury.

6. CONCLUSIONS

A simulation analysis of a fish processing plant aboard a common factory ship has been presented. In doing so, a discrete event simulation of the global process and a precise digital human model of the bottleneck operation have been developed. As a result, those parameters affecting the overall process efficiency and the wrapping operation –the actual bottleneck- have been identified. A set of key performance indicators has been defined to evaluate the process efficiency under three different scenarios. Some organizational effects have been found in the last stages of the process, i.e. a decrease in the resources utilization due to the product size variability. An exploratory analysis to assess an alternative organization has been carried out. Finally, an ergonomic and operational analysis of the wrapping operations is presented as a means of improving both the working conditions and productivity.

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