Study and analysis of production dynamics with designed experimentation: sizing of a pull drum line supermarket

R. Di Micco, E. Romano, L.C. Santillo

***Abstract*—** To implement the strategy of the continuous flow process the goal is to aim to "Interdependent connected Processes" adopting the Pull System methodology in the Just in Time production environment. This logic is an ideal to tend, in which each individual operation is carried out only if necessary and if requested by next operation, in order to avoid overproduction, which is the worst waste.

This logic brings to a "pure" Pull System that is where the process is triggered by the customer request, going backward steps along the upstream up to raw materials supply. Pure Pull Systems are possible in theory but are very rare in practice. For example in manufacturing production situations in which the order is completed by forecasts sales at least at the beginning (push/pull systems) are most common.

These production systems therefore represent a model of operational excellence, which represents a target for PUSH systems. You want to produce a single piece at time, transferring it from a process to the next without waits. But process "links" means reducing the lead time and waits, getting to a flow that extends itself as the process reliability improves and waiting times such as set – up decrease. There are, however, areas where the flow is not practically possible, for example because numerous set-ups are needed or because "providers" do not send one piece at a time, working in batches. In this case you can control production implementing Pull/Push interfaces. A first solution is a system based on kanban that reintegrate a downstream station, known as "supermarket pull", where the continuous flow is interrupted and the process upstream works in batches according to a "pattern production", with a production managed by a wheel system, that is with a sequence set by the same upstream department and it is based upon a yearly model forecast of production suitably agreed among Marketing, Development and Production.

The creation of the model, its verification and its validation are explained in order to give an overview of the utilized model for further investigations.

***Keywords*—** Simulation, Supermarket Pull System, Kanban System, Critical thinking, Sequential learning, Inference Space, Degree of Belief, Active Factors, Pattern Production Schedule.

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I. Introduction

In modern environments, characterized by high complexity and turbulence, the traditional Ford-like approach of uncoupling production with the market, father of the mass production, cannot work anymore. The lean production aims to make manufacturing and market moving at the same time using a set of management techniques that will give the start to the following approaches: Just in Time, Total Quality Management and Concurrent Engineering. The Japanese experience has shown that the most critical aspect is not related to the specific technological feature, but is related to the organization of the manufacturing process flow. The lean production allowed an improvement in terms of flexibility to new market requests (range of the responses offered ex-ante), moving this task on the multi-capability of the workforce and rearranging, with flows and processes, the overall enterprise activity, from development to manufacturing and finally to the distribution. It can be noted that there was an increase also of time flexibility thanks to a slight usage of the industrial automation. The same continuous product innovations are helped by the integration of the new flexibility features and of the human resource involvement, generally arranged in inter-functional teams, in problem solving activities, becoming them a competitive advantages for the Corporate now capable of reengineering the organizations according to the new criteria. The philosophy of the waste hunting is based on the main principle of creating a "Continuous Process Flow". A strategy to implement this goal is to create "Interdependent connected Processes" using "Pull System" approach that is strictly related to the Just in Time production idea.

The objective of the "continuous flow" is the waste elimination in every phase, also known as "one-piece-flow". Production of one piece at time is the target, obtained moving it from one process to another without waits. Connecting processes means lead time and waits reduction: therefore the flow is extended more and more as the process reliability increases and the waiting times like set-ups decrease. Moreover, there are areas one-piece flow is not possible, e.g. when frequent set-ups are needed or because suppliers send parts in batch. In this case the planning (push approach) should be avoided because it would mean only estimating without knowing what the next process or customer in reality need. On the contrary better results are got implementing Pull/Push interfaces; a first solution could be a system based on "replenishment" kanban system supplying "downstream processes known as:

- *Supermarket Pull,* where the continuous flow is broken and the upstream processes are working with lots following a "pattern production", i.e. a fixed sequence from the upstream production area itself. This approach enables to control the production among the flows and aims to supply accurate instructions of production to the upstream processes without planning based upon the potential downstream requests.

When it is not possible to have a product stock, because of the high customization requested or for the high costs or for phase-out matters, or when we got a better synchronization between up and down streams, we have the following available options to the supermarket pull system:

- *Sequenced Pull*: the supply process produces a fixed quantity in a fixed sequence from the downstream shop directly in front of an order from the customer process (JIS, Just in Sequence).
- *Fifo lane* (or *FiFo sequenced* or *ConWip*): it contains constant quantity in stock in a FIFO sequence and it is placed between the upstream supply process and the downstream customer process. Hence, if the lane is full the first process should not produce until the second one has not used parts of the available stock. In this way it is avoided upstream process overproduction.

In the Supermarket pull system, the Kanban is a signal of product availability that needs to be managed. Each product range should be stored in a well delimited area or in a rack. We generally speak of "Supermarket" that could be managed in a way that a visual check of parts availability could be easily carried out. The stock level among the different products is directly connected to the kanban number running around; the main objective is to minimize the number of Kanbans used.

The scope of this work is the complete re-organization of production flow according to the Lean Thinking philosophy for the industrial applications [25]. The complete re-organization implementation of material flow management has been performed through the supermarket sizing for which the logic of the reintegration kanban has been adopted.

Based upon the above considerations, a supermarket design activity was kicked off, taking advantage of the cooperation of Naples University and Six Sigma Department of Whirlpool Europe Naples Factory. The model of the Naples production Factory was fully developed in Arena SW environment. The model was developed having broadly discussed with Subject Matter Experts, Supervisors and Operators, in order to better reproduce the real process working nowadays. Following up the OpEx approach, based upon the ideas of Critical Thinking, Sequential Learning, Inference Space and Degree of Belief of the applicability of a specified process solution, we directed our investigation towards 3 main objectives: finding out the suitable size of the supermarket that could better serve the PULL production with all the relevant constraints of the current Factory available areas, validate the model that should represent the dynamics of the daily production, find out clues and indications about potential production issues, increasing the relevant level of knowledge and then create potential countermeasures, where the findings got from the investigation process match with engineering knowledge [18].

The pull technique of only producing what is required when it is required is used in the kaizen work phases. The results are less rework and scraps, lower work-in-process, reduced lead time, increased throughput rate and higher service level. Other tools such as standardized work (Cudney and Fargher 2001) [1], quick changeover (Van Goubergen and Van Landeghem 2001; 2002) [2], 5S (Henderson and Larco 2000) [3], etc. can be referred to the works in the reference. In most of the companies, new concepts are hard to be introduced. Simulation has proven to be a powerful eye-opener (Van Landeghem and Debuf 1997; Van Landeghem 1998; Whitman et al. 2001) [4, 5, 6, 22, 23]. By combining simulation with the DOE, we aimed to achieve faster adoption and less resistance to change from the workforce. Simulation models are built up using computer software and applied to the real world cases. Simulations are used to model manufacturing processes for a core product family and to validate the evaluating alternative scenarios.

Generally, simulation is a tool in the implementation of lean manufacturing and it can be used for the manufacturing shop floor directly. The model simulation software used as a testing environment and support to decision tool, could be applied in a phase when the real system is still under preparation and could support choices in order to better satisfy the demand of the customer (external and internal), because the team can easily prioritize the different process solutions proposed, before any change is actually carried out. For the simulation project the Arena modeling system 8.0.0 [24] from Rockwell Software Inc. was used. Arena is a discrete – event simulation in which mainly entities are used as objects under a particular process. Random Noise is embedded, allowing better simulation of real scenarios of manufacturing processes.

II. Experimental analysis

Using Critical thinking approach, we let our work led by questions and started to define which are the potential aspects or factors that could affect the production life in terms of produced parts and WIP essentially.

To collect meaningful data, we tried to figure out the causal relationship between factors and chosen outputs using the Design of Experiment (DOE) approach manipulating factors at 2 different levels to see their effects, because "No Causation without Manipulation" (Wang).

Sequential DOE's were performed according to increased level of knowledge gained, following up the PDSA Deming cycle, all of them using PC-based simulations.

First of all, it should be said that the year production of the

Naples factory could be divided in 3 different Timeframes (1-2-3), according to the ramp-up timeline. Within each timeframe, a specific production wheel that manages the drum code production (dividing codes in runners, repeaters and strangers) could be defined. Six drum codes were considered (runners).

We started the first simulation DOE (DOE1) to familiarize with the approach for people not used to working with it, in a simple but representative case: Timeframe 1 (from January to April 2008), planning a Full Factorial (FF) DOE, avoiding the first time to work with an alias structure. A 32 run FF DOE was planned and executed, manipulating 5 factors (supermarket size, standard deviation of the probability distribution of the Wash Line production, *Takt* time of the Wash Line, Shift of the Drum Line, Production Lots). We could have planned a FF DOE because no real sample could be wasted.

The outputs measured were: # of processed parts (*Parti Processate Variable*) by the line, WIP, Total n° of elements in queue, waiting times for each drum code, # of times each specific drum code went in kanban red zone (under-stock).

Before the DOE was really carried out, a Prediction Table was discussed among the Team (including Process experts) in order to foresee which could have been the impact of each factor selected on the defined outputs, the potential factor best settings and the theories behind each choice. Whirlpool Six Sigma approach is based on the research of the active factors: Statistical significance is used only as suggestion and should be crossed with theories and engineering predictions to say we learn about cause & effect relationship.

The relevant Factor Relationship Diagram (FRD) was also drawn, to show how the experiment was run and the relevant run order randomization (applicable because of the random nature of the specific model simulation). The data analysis was conducted in 3 different steps: Practical, Graphical and lastly Quantitative, following the Ross' Rules of Analysis (Six Sigma Associates Company registered approach).

Basing upon the basic hypotheses of the model (influencing Inference Space and Degree of Belief), and using the engineering predictions, indications about the above chosen factors influencing our outputs were found. This helped the Team to guess upon a potential Supermarket of a size of about 4000 drum parts. Besides, the findings on WIP, Processed parts and the other outputs helped us to better focus on issues and potential bottlenecks to be looked after. The most important aspect was the good accordance of the model simulation findings with real scenarios. This meant that the model worked well and could be used as a basis for making behavior predictions. Because the first model was based on the greatest restriction of being focused on only one Timeframe, a new tuned up model was built. In this new model, the production management was extended to the full year planning, simulating other features (e.g. modifiable Changeover, Conditioned maintenance, 2 Washing Machine platforms) that put the model in the position of being able to better represent a real manufacturing dynamics. Drum codes were updated, according to new range extension (passing from 6 to 11 codes). This reflected on an increased Inference Space and relevant Degree of Belief. Basing upon the results of the previous experiments, and trying to simulate also some bad working conditions, a sequential DOE was planned [26]. The DOE defined was a Fractional Factorial $2_{IV}^{(6-2)}$ in 16 runs. A Resolution IV DOE was chosen in order to reduce the time needed to complete the simulation and the belief that only Main effects are important. If interactions will appear to be Statistical Significant, the engineering knowledge was supposed to be high enough to correctly interpret them. As done before, a Prediction Table with factors, levels and theories was again prepared. In addition to the FRD inclusion, the relevant alias structure (with the Defining Relation and Confounding Patterns) was analyzed to better clarify which information was lost. Running a Resolution IV design means that the Main effects could be studied without any issue because they are confounded with 3-way interactions, while the 2-way interactions will be confounded with other 2-way interactions. This could create interpretation issues. DOE was planned and executed, manipulating 6 factors (OEE, supermarket size, *Takt* time of the Wash Line, Shift of the Drum Line, Changeover, and Conditioned maintenance). The outputs measured were: # of processed parts by the line, WIP, # of times each specific drum code went in kanban red zone (under-stock), Manufacturing Lead time for 470 & 490 Washing Machine Platforms, Fill rate and # of times each specific drum code went under kanban red zone. The data analysis was again done in 3 different steps: Practical, Graphical and lastly quantitative.

Basing upon the basic hypotheses of the improved model and using the engineering predictions, indications about the above chosen factors influencing our outputs were found. The findings confirmed the directions ("Where to work" questions) indicated in the first familiarization DOE in terms of Supermarket size of about 4000 drum parts and helped us to simulate scenarios also in really critical working scenarios (very low OEE), coming out with suggestions to help the Team to find out robust solutions that could help to support Manufacturing organization in worst working conditions. This second DOE also showed that the simulation model had better reproduced a real production day. This had shown the power of the Sequential Learning approach and of the Cause/Effect mindset. At the end, even though a Supermarket pull size was settled, after a Technical Review with Process engineers, it was shown that space availability issues could arise. This put the Team in the conditions to find out another size, doing another simulation DOE, trying to find out the best fit to the space issue need. Following up the directions from DOE 1 and 2 and funneling on factors used in the first 2 experimentations, it was decided to run a DOE 3, Full Factorial with 3 factors in 8 runs. Factors used were: OEE, Supermarket size, Takt time of the Wash Line. The outputs were limited to WIP and manufacturing Lead Time of 490 Washing Machine Platform (because the most requested in the Factory product in plans). Prediction table and relevant FRD were ad-hoc generated. The results confirmed the already seen direction and enabled the Team to define that the Supermarket size with 3700 slots fitted well with production dynamics and requests of space availability. Summing up, key learnings were: to funnel to a robust solution against potential uncontrollable scenarios, Critical thinking and Sequential Learning will support in finding out solution faster. The Cause and Effect mindset, supported by designed experimentations helped to find the active knobs that manage the life of the Manufacturing. DOE's in simulation environment will be of great help especially in early steps of the investigation paths, also because the cost of simulated DOE's does not impact the creation of real parts: it is a best practice thoroughly applied in every activity of design in Whirlpool development.

III. Problem Formulation

Naples Factory produces Frontloader Washing Machine. The main production phases of the primary processes are:

- Drum codes production;
- Assembly lines related to the production of the drum, cabinet and front panel;
- Distribution that is the Inventory of the washing machines produced, waiting to be shipped to RDC (*Regional Distribution Center*).

Currently the drum production is carried out by an automatic line having a cycle time of about (Tc) 12 sec. and with a production capability of about (Cp) 300 pcs/h. The drum produced by the above described line, is transferred to suitable metallic racks in lots of 48 pieces, with relevant transportation, on the *Washing Unit* Line. Its production parameters are: Tc = 11.25 sec. e Cp= 320 pcs/h. In the assembly shop, there is an in-coming goods area in which components coming from the supply chain are placed. Those components are then delivered towards the inventories of each area using forklifts.

The mounting is done on 2 parallel lines called:

- Assembly Line 1;
- Assembly Line 2.

The choice of implementing this managing strategy to redesign the material flow according to Lean mindset in the area of the Shop floor highlighted the need to introduce a supermarket in the upstream of the *Washing Unit* (W.U.). This will enable to uncouple the drum and washing machine manufacturing phases. Deeming that the Pacemaker is in the W.U., the perfectly W.U. time synchronization with the Assembly line is got only if we introduce a Supermarket System through Washing Unit and Assembly Lines. The model, implemented in the Arena Rockwell Software 8.0.0, translates every production processes. It implies [18]:

- Drum creation;
- Storage in the supermarket;
- Washing machine creation as signal for the withdrawal from the supermarket and the match between withdrawal order and availability with query to the Kanban rack.

From the 2008 Forecast Analysis, coming from Material Management (MM) Department, 18 codes were identified. They could be gathered in 2 macro families related to the dimension of the drum diameter. Finally 3 different Timeframe for the forecasts according to sizing the supermarket, were identified. The identification of the 3 Timeframes is due to the market request variation, during which some codes more than others are foreseen to be requested and produced (runners).

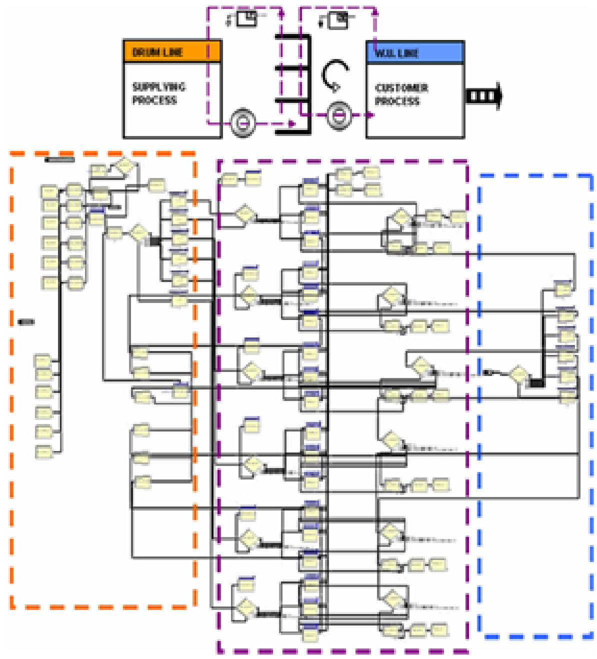


Fig. 1 Flow Chart of Arena Model

The flow chart of the manufacturing cell can be seen in Fig. 1. As it can be clearly seen, the simulation model includes three main areas. Firstly, there is the order release logic (washing machine creation), which is responsible for managing the orders for the second area which is the assembly process. Within the assembly process, all parts are put together, tested, packaged and then finally delivered to the customer.

The parts for the assembly are directly taken from the buffer called supermarket, where every in-house produced part for each product is kept. This buffer is replenished by the drum machine area (drum creation model).

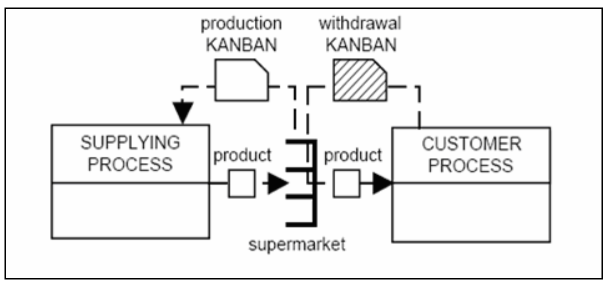


Fig. 2 Flow Chart Replenishment Model

To easily explain, the entire supermarket logic can be divided into two parts (see Fig. 2). Firstly, there is the buffer function and the order forwarding parts, where parts basically arrive from the drum creation process and where they are kept in their specific buffer rack. For every part considered in the simulation, one buffer was assigned in order to track each part stock differently. During the run, the buffers of each part are refilled by the drum code process. Before the parts for refilling empty space are actually put into the buffers. The throughput time of the replenishment process is then evaluated. As soon as the signal for the supermarket is released, one batch of 48 parts is emptied. The replenishment logic within the supermarket subroutine as shown in the same Figure 2, represents the process performed by the kanban system in the manufacturing cell.

The kanban system which adopts the pull system requires sending the information of the kanban in order to give the start to the upstream processes in the system. The signal and hence the kanban, coming from a downstream workstation and directed backwards can be modeled therefore as an entity or as resource.

IV. Methodology

The first step of the investigation was done simulating scenarios working on the *Timeframe 1* (January to April 2008 planned production) only, because at that time it was the most consolidated information available in terms of Market requests. Basing upon the model assumptions and work hypotheses, we decided to run a structured experimentation using DOE approach, overcoming the Trial & Error methodology, trying to figure out the causal relationship between the manipulated factors and the outputs of our interest [10, 11, 15, 16]. In this scenario it was considered that there are 6 codes all belonging to the 473 (drum diameter in millimeter) family. Changeover related to transition from 473 to 490 families was therefore not considered. The following manufacturing parameter values were then considered and used for the simulation With an Availability of the plant at 94%, an Available time of 7,5 h can be obtained, where the drum production shift lasts 8 h. This means that an Uptime of 90% can be reached. This brings to 405 min of real production. So the O.E.E. is 82% (with the quality index equal to 97%). The designed experimentation adopted was generated using the Standard Order 2^n Design, defined by Yates. The “n” (number of variables) is used to determine the minimum number of experiments needed to run and the number of initial columns in a design. Coding used for these designs will be as follows: “-” = low level of a factor & “+” = high level of a factor. [9, 10]

The first DOE (DOE1) carried out was a Full Factorial (FF) DOE on 32 runs. The FF design is a type of experiment that tests every possible combination of factors at a given number of levels (in this case 2 levels only). The idea is to try to simulate possible failures and/or bottlenecks during the daily production, assuming that the Supermarket is already present in production, under specific efficiency conditions of the lines, as detailed before.

The reason why we used a FF DOE at the beginning of the investigation was to start familiarizing with the model and begin to increase our level of knowledge about potential production dynamics in which a *Pull Supermarket* (it will be called buffer in our experimentation) is installed in order to decouple the production of the New drum line with the production of the 2 parallel lines for the Washer assembly (WASH LINE), L1 & L2, leveling production and improving its predictability. Besides, FF DOE’s do allow to study all the available information (main effects, interactions up the highest order – called degrees of freedom), without loosing anything. It means that we do not have to take care about confounding and aliasing of the effects (that is something that is related to Fractional Factorial DOE’s) [10]. The first DOE was FF because the level of knowledge about the model dynamics was not so high at the beginning: potentially important interactions could have been really difficult to be interpreted. Finally, the 32 runs were done in SW environment that means they were almost for free (apart of the time spent for the simulations running). For this reason the DOE1 and all the other simulations were carried out without any restriction of randomization (Experiments are called Completely Randomized Design or *CRD.* The Randomization is applicable because of the noisy nature of the Arena simulation environment) [17].

V. DOE 1 Experimentation

Before the DOE1 was executed, there was a planning phase, in which it was defined:

1. Responses to be studied;
2. Factors to be manipulated and their levels;
3. Predictions about factor’s effects on the responses, level of importance and theories behind,
4. The way the experiment was run thru’ the Factor Relationship Diagram (FRD) [7].

The information in the points from 1 to 3 was gathered in the DOE Acquisition form [19], from which an extract was reported in Fig. 3 and 4

Main Response Variables	
Y1	**Parti Processate - parts processed by the lines L1 and L2.**
Y2	**WIP (elementi in coda) - parts phisically present in the Supermarket.**
Y3-Y8	**Tempo attesa code (i) in hours ->The next 6 outputs are related to waiting time related to the runner codes of the timeframe 1. We have 6 codes of the drums that are relevant to the wheel management. There is a waiting time before a drum is processed by the Wash Lines.**
Y9	**N° elementi in coda totali – it is the sum of the parts present in the supermarket.**
Y10 - Y15	**Zona Rossa code (i) ->It measures how many times one code of the wheel went in red zone of the slots of the supermarket.**

Fig. 3 Main responses

Factor	(-1)	(+1)	Predicted Best level	Predicted Importance (H - M- L)	Theories
buffer	2016 parts	4176 parts	4176 parts	H	If we have a bigger buffer, we could have a better leveling of the production.
dev std takt time	normal distribution with mean 11.25 sec and std dev of 1 sec	normal distribution with mean 22.50 sec and std dev of 5 sec	not easy	L	Probability distribution of the way the Wash Line produces (we simulated 2 parallel lines working) – we are referring to takt time. Not easy to foresee. Tested to introduce random noise in the experiment. Standard deviation based on historical database of the Industrial Engineering Dept.
takt time L1/L2	320 pieces/hour (11.25")	160 pieces/hour (22.50")	320 pieces/hour (11.25")	H	Common sense and manufacturing people experience say more parts processed and less waiting time when lower takt time.
Shift drum line	2	3	3	M	From the experience, with more shifts we can keep production coverage safe.
Lot	48 drums	1488	not easy	not easy	It is related to the part lot connected to the Timeframe1. Not easy to foresee behavior.

Fig. 4 Prediction Table

The rational behind the wide usage in Whirlpool OpEx approach of experimentation is that DOE is a way to answer to questions with manipulation of factors, in order to drive the discovery work and find new directions for investigations. Behind each chosen factor/level there was a theory and/or a current belief to be proved and/or disproved with our DOE. Hence a great focus is placed on the definition of predictions for each factor in order to see whether the predicted behavior (that represents the current process knowledge) is confirmed or not. With DOE's, that will be analyzed using Pareto's and Normal Probability Plots (NPP), it is not only looked for Statistical Significant Effects, but for Active Factors. An Active Factor is a manipulated knob that gathers together 2 main features: its effect is statistically significant and its behavior matches relevant predictions.

Statistical Significance is only used as suggestion. This should be done also for potential significant interactions. In this case, the current level of knowledge did not allow us to work it out.

In Fig. 5, the DOE1 FRD is displayed. It would allow to everyone (even not present) to fully understand how the experiment was run.

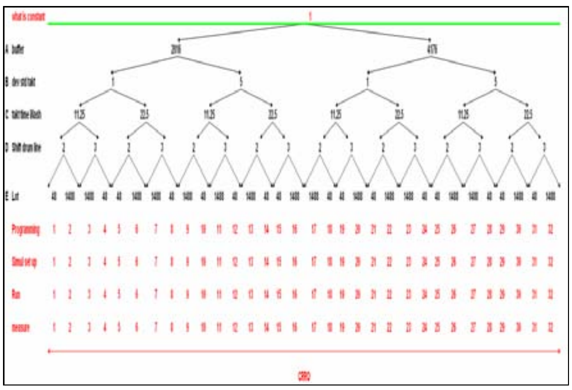


Fig. 5 FRD

The upper line displayed is called *Line of Restriction* (LOR). [17] It delimits what is constant in the experiment and whether any restrictions on randomization were present. It helped to evaluate the relevant Inference Space (the area within which you draw conclusions based on the results of your experiment) of the DOE and helped to increase the relevant Degree of Belief (practically speaking it means, when there is a need to study about a process or a product in which there is a mean (location) or variation (dispersion) issue, the level of "certainty" that a modification/change (i.e. action) will really result in an actual improvement in location or dispersion). The Degree of Belief cannot be quantified and is related to "The extent to which an experimenter has drawn his conclusions from an analytical study" [8]. So it is related to predictions.

CRRO (Completely Randomized Run Order) is the way the runs were carried out.

After the preparation of the relevant DOE matrix, data was collected and the analysis started. The approach to the analysis follows the ROSS' RULES OF ANALYSIS [9]: *Practical*, then *Graphical* and lastly *Quantitative*. Specific attention is put on the first step, before doing any statistical analysis, done to see whether the results are of any practical importance. Findings for the most interesting aspects are summarized below by the two most interesting variables:

- *Parti processate*, which represent the drum code number that the system can process;
- *WIP*, work in process.

A. Parti Processate Variable

Starting with Practical approach and sorting the data from the Min to Max value, it was noticed that the level boldness of the factor lot is "too much". On 1488 value, no *Parti processate* variation was noticed: 1488 value is not of any practical meaning. The attention was then focused on data corresponding to 48 lot value (Fig 6). Look at key signals, using Pareto, Rank & Residual analysis, Main effects and Interaction Plot [10, 13, 16]. (see Fig 7, 8-1, 8-2)

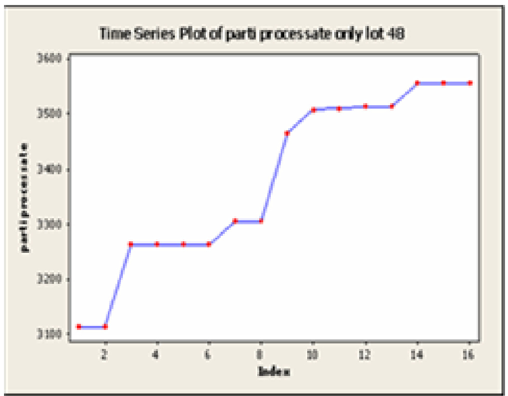


Fig. 6 Time Series Plot

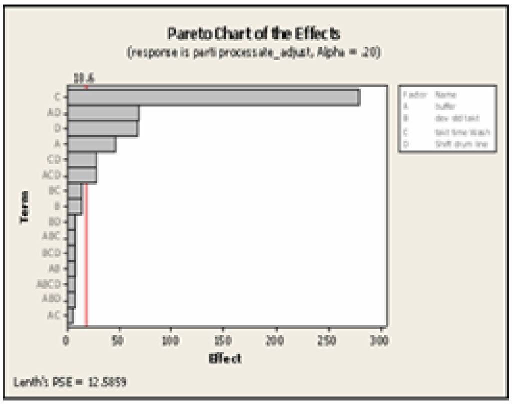


Fig. 7 Pareto Plot

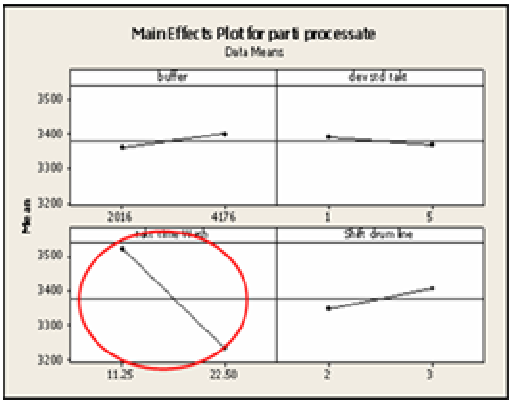


Fig. 8-1 Main Effects Plots

Not considering relevant the 3-way interactions (least likely to occur), results could be summarized in this way: reducing *takt* time of the wash lines, it will increase the n° of *parti processate variable*. Less std deviation of the takt time will help to increase the n° of *parti processate variable*. With more shifts, more *parti processate* are available. More *parti processate* if buffer with 4176 slots. In terms of Interactions, the most interesting aspect is that with buffer at 4176, a robust working condition vs. the # of shifts is available. All the predictions were matched (see Fig 8-2 for Interactions).

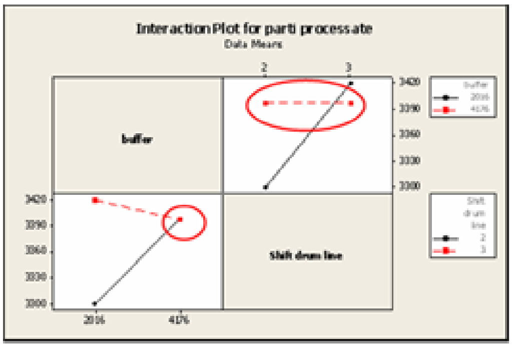


Fig. 8-2 Interaction Plots

B. Work in Process (WIP) Variable

It was faced the same issue on variation created in the DOE with lot at 1488. Only the key signals are taken from the analysis (having used also Model building, data adjustment and Box-Cox power Transformation) [10, 14], using only the statistical significant effects and relevant active factors (Fig 9). Remember that WIP works in opposite direction than *Parti Processate Variable*.

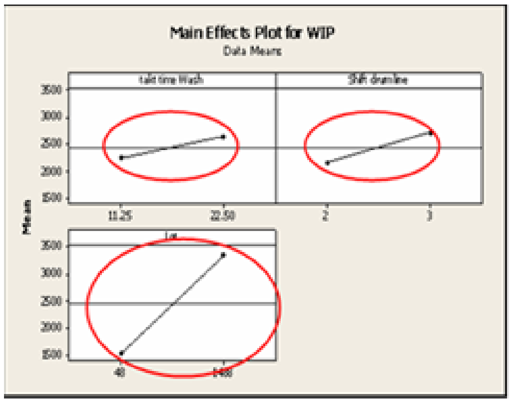


Fig. 9 Main Effects Plot

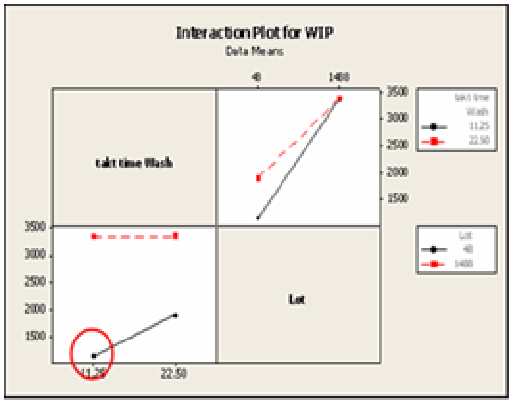
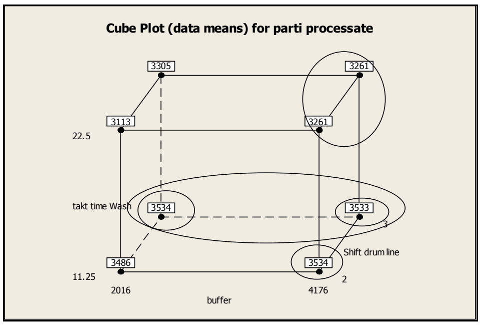


Fig. 10 Interaction Plot

In order to reduce the WIP the settings are: E = Lot; D = Shift Drum Line; C = *takt* time Wash at minus value (48 – 2 – 11.25 sec). On Interaction plot, the only lines that were not really parallel are related to interaction CE and DE. Both of them indicated that to reduce WIP it is needed to move to at least minus setting of Lot and Shift drum line and takt time Wash. At Lot equal to 1488 there is a condition in which the system independent from the takt time Wash, but it does not make any practical sense (see Fig 10).

A short discussion could be done for a 3-way interaction ACD=buffer**takt* time Wash*Shift drum line because it was statistical significant for both *Parti Processate* variable and WIP outputs (Fig 11).



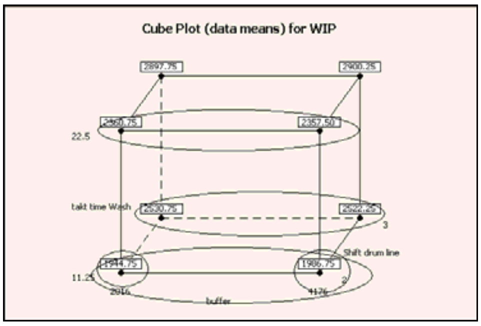


Fig. 11 Cube Plots for ACD

From ACD plot we say that we need to work on shift drum line at 2 to be independent from buffer and *takt* time wash and minimize the WIP. It is in the opposite direction related to the *parti processate* output that asked for shift drum line to be placed on level (3 shifts). It could be considered a possible trade off opportunity to satisfy both the conditions, because at shift drum line at 3, the WIP is not so high and is robust to other parameter variation more than on minus level.

VI. DOE2 EXPERIMENTATION

Because as Sir Ronald Fisher once said that "The best time to design an experiment is after you have done it", to increase the Inference Space and the relevant Degree of Belief, a sequential experiment was planned, spinning again the learning PDSA cycle, asking new questions to be answered. [20]

Next steps of investigations regarded the following areas:

- confirmation of most of the signals coming from the first simulation;
- drop out *takt* time std deviation or at least change the level settings;
- change the level setting of the LOT, replacing the 1488 with another more feasible and real value, in order to create more variation and have more reliable signals;
- check of the n° of assumptions made for the creation of the first model, in order to allow things to vary and simulate Manufacturing process in bad working conditions, like low OEE, different possible supermarket sizing, or other vital manufacturing line parameters;
- get more variation of how many times one code is going in the red zone and cross this result with drum line shifts;
- test the model with other productions timeframes (the first simulation valid only for Timeframe 1).

To explore the above described areas, and using more accurate information about market requests and having gained more knowledge about drum line dynamics, we refined our simulation models, making it more general. Now the new simulation environment worked on a more generally defined Timeframe that is extended to the overall year production. New introduced drum part codes are considered. There were 11 codes: 6 in the 473 family and 5 in the 490 code family. Downtime was considered as well. It could be evaluated taking into account that in one shift it can be decided to run one Changeover and a second one across the second shift (30 min in total). Besides, one maintenance operation that takes away 15 min is included. Furthermore in this case it has been suggested a constant set up in the transition from one code to another. It can be reached an Uptime of 76% that, given in minutes, brings to 300 min of real production. It has been suggested two threshold values for O.E.E.: 69%, based on Uptime equal to 76%, 97% of Quality and 94% of Availability; and an O.E.E. of 46% based on 50% of Uptime.

The DOE2 was a Fractional Factorial DOE 2^{6-2}_{IV} on 16 runs. [10, 16] The Fractional Factorial Design was used for 2 main reasons: test more interesting factors in a screening fashion design; limit the # of runs to 16 in order to save time even though the experiment is run with simulation (now the model familiarization level was increased). A Resolution IV design means that 2-way interactions cannot be *cleanly* interpreted, because they are confounded with other 2-way interactions. But looking at the results of the previous DOE, interactions were not so strong and increased engineering knowledge induced us to suppose that only main effects (that are confounded with 3-way interactions at least) were expected to be the knobs driving the variation in the simulated process. The essential steps for the DOE2 planning are reported below (Fig. 12):

Factor	(-1)	(+1)	Predicted Best level	Predicted Importance (H - M - L)	Theories
OEE	46%	69%	69%	H	Better overall process perfomances with higher OEE. 69% of OEE is calculated based upon 0.94 of availability, 0.97 of quality and 0.76 of Performance (AxPxQ). 46% of OEE is got with P=0.5.
buffer	3168	4416	4416	H	Indications of the previous DOE says that we have to work towards 4416 buffer size.
takt time L1/L2	120 pieces/hour (30")	320 pieces/hour (11.25")	320 pieces/hour	H	Indications from previous DOE and common sense say more parts processed and less waiting time when lower takt time.
Shift drum line	2	3	3	M	As above.
Conditioned maintenance time	15'	80'	15'	M	Less maintenance time, better productivity. Values of the levels taken from last 3 months collected data.
Changeover time	7'	13'	13'	L	less changeover time, better productivity. 7 minutes for each code change and 6 minutes including the taking away parts during the change of the job.

Fig. 12 Prediction Table

Compared to DOE1, new variables were added:

- *Man_Lead_Time_473(h)* and *Man_Lead_Time_490 (h)*, are defined as the manufacturing lead time per drum dimension code family;
- *Fill Rate* is defined as the percentage of demand satisfied.

The key signals for the selected responses reporting some important graphs are summarized. Analysis flow will again follow the 3 steps: Practical, Graphical and Quantitative.

A. *Parti Processate Variable*

From a practical standpoint, it could be seen that takt time is expected to have an influence on the response under analysis, as it could be seen from sorting data and plotting them on the a Time Series plot (not reported here).

After a comparison of Statistical Significant effect analysis on raw data, ranked data and Box-Cox power transformation analysis, we got the following signals (see Fig. 13-1, 13-2), in which we referred to *AC= OEE x takt time* interaction, after having looked at confounding pattern and referred to suggestion coming from Effect Heredity principle (Occam's Razor principle) to interpret 2-way interactions together with the mostly important *Engineering Knowledge*. [13]

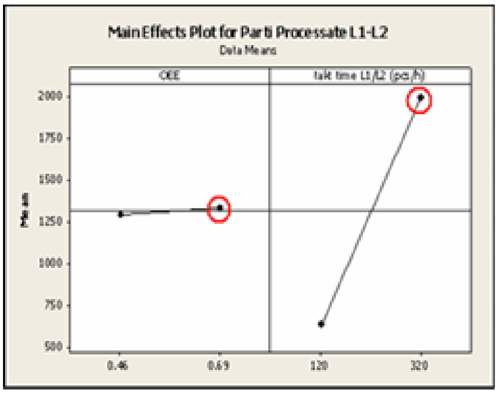


Fig. 13-1 Main Effects Plot

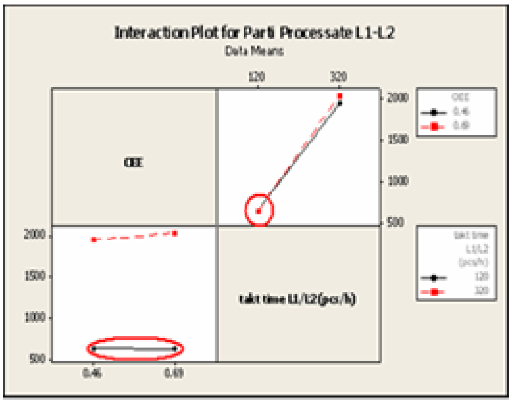


Fig. 13-2 Interaction Plot

It was clear that to have more parts produced it is requested to increase the pace of the lines and reduce the takt time. In terms of the other 2 factors, it could be said that OEE had a slight influence because fewer drums implied less machines produced. Both takt time and OEE seemed to meet predictions that implied that they were active factors. Summarizing, including a slight significant effect (Changeover time) to improve readability, it could be seen that:

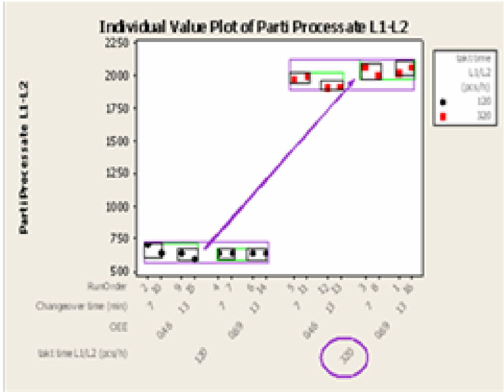


Fig. 14 Individual Value Plot

To have more parts produced it is needed to reduce the takt time. OEE on 0.69 meant a potential variation reduction in the produced parts. Finally it could be noticed that if Changeover times is set at 7 minutes it could be got the same results on the 2 different OEE values, this means conditions of Robustness vs. OEE reductions.

B. *WIP Variable*

From a practical view, there was a suspect of active higher order interaction than main effects or an outlier presence (that could be recovered with suitable rank transformation). [12] Working with Model Building and Data Adjustment, we confirmed the outlier in the observations (se table below):

Obs.	*Std.O*	*WIP*	*Fit SE*	*Fit*	*Resid.*	*St Resid*
11	11	3681	5773.8	293.9	-2092.8	-3.42

TABLE I - STATISTICAL PARAMETERS

Then, only Statistical Significant effects are then reported and looked at (Fig. 15-1, 15-2):

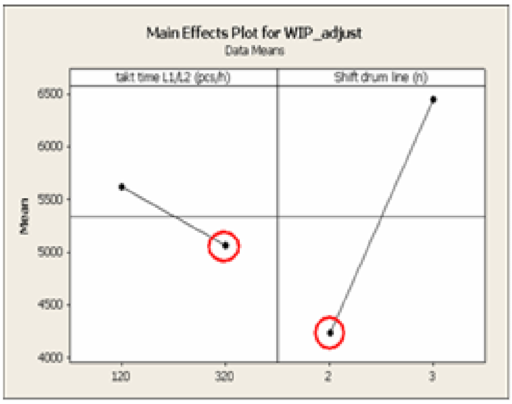


Fig. 15-1 Main Effects Plot of the adjusted data

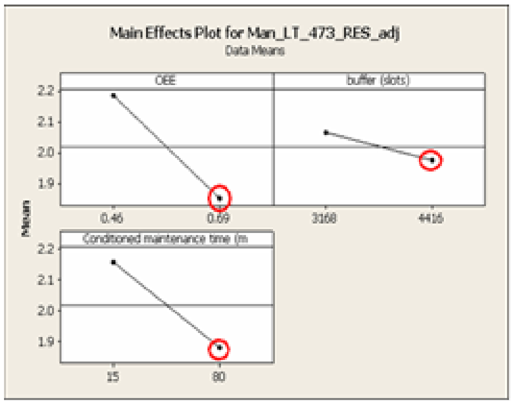


Fig. 16-1 Main Effects plot

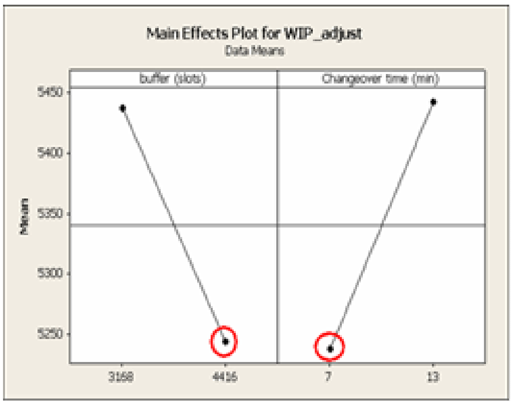


Fig. 15-2 Main Effects Plot of the adjusted data

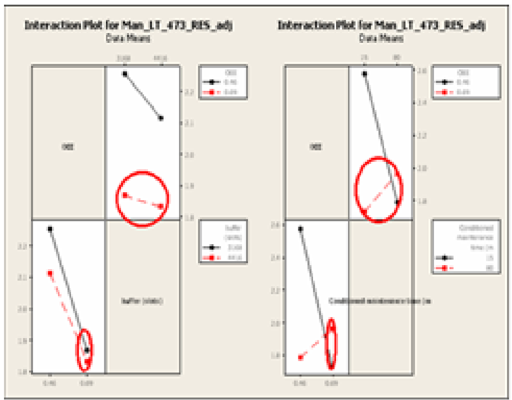


Fig. 16-2 Interaction plots

To summarize: to reduce WIP it is needed to reduce takt time and use 2 Shifts, use buffer with more slots (4416). This will allow having less material moving around. Changeover time reduced (7 min) that will bring the manufacturing to work with less safety inventory. Working with 2 shifts, WIP kept quite constant even though in front of a great OEE variation (the relevant Interaction plot is not reported here, because it showed almost parallel lines).

C. Man_Lead_Time_473 (h) (Manufacturing Lead Time) Variable

An outlier was immediately noticed in the dataset and adjusted with different data mining techniques like gap offsetting [14], Residuals and rank. [10, 12] Key signals coming from data analysis are below reported, with some plots (Fig 16-1, 16-2).

Interactions have been selected firstly according to the engineering knowledge and then using the aid of the Effect Heredity principle [13]. To reduce the Lead time it is needed to work in the following directions. Main effects:

- bring OEE to 0.69;
- use bigger buffer with 4416 slots;
- increase the Conditioned Maintenance time at 80 min, even though this indication is against the practical engineering and will not be followed (it could mean masking issues).

From interaction standpoint it could be said:

- Increasing OEE we are able to reduce and keep the lead time quite constant.
- OEE helps a lot in reducing the relevant Lead time. With a higher OEE, Lead time is reduced and concurrently it could be found a condition in which the system would be independent from the buffer size. Less variation of Lead Time is achieved when OEE is at 0.69 (see also final summarization in the next Fig 17).

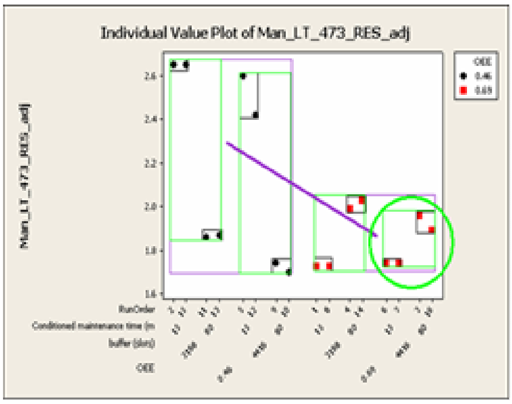


Fig. 17 Individual value plot

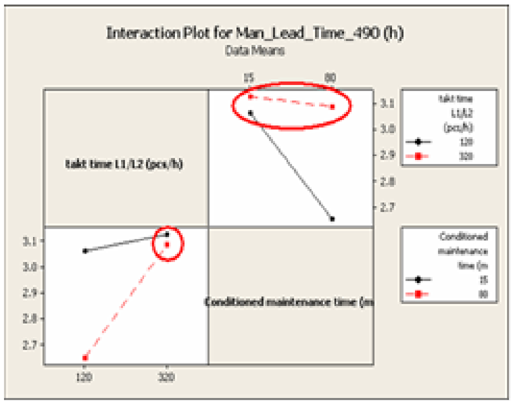


Fig. 18-2 Interaction plot

D. *Man_Lead_Time_490 (h) Variable*

Taking the key signals from the graphical analysis, we will get the following key feedbacks regarding the Manufacturing Lead time, comparing raw data and ranked data. Using the confounding patterns and engineering knowledge, the effects selected were: OEE, Changeover time, and Conditioned maintenance. The following 2-way interactions were therefore included (in parenthesis the selected interactions):

- OEE (%)*buffer (slots) -> [takt time L1/L2 (pcs/h)*Conditioned maintenance time (m)];
- [takt time L1/L2 (pcs/h)*Shift drum line (n)]:
- OEE (%)*Shift drum line (n) -> [Conditioned maintenance time (m)*Changeover time (min)].

Only the most important plots are shown here (Fig 18-1, 18-2, 18-3):

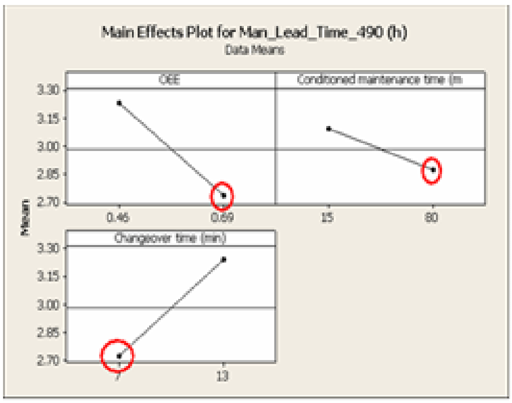


Fig. 18-1 Main Effects plot

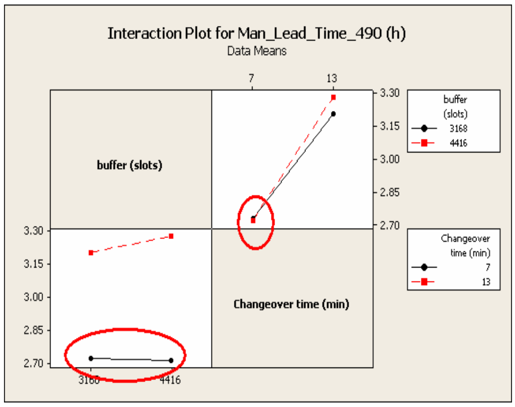


Fig. 18-3 Interaction plot

After having checked Residuals with the above effects, a good R-Sq (adj) = 70% was found. Not taking into considerations indications coming from the Conditioned Maintenance (that even if physically reasonable, are of *no practical meaning*), it could be said that every predictions is matched and then the following conclusions could be drawn:

- Main effects: OEE at 69%. Changeover time is to be set at 7 min.
- Interactions: Lower takt time (320 pcs/h) => less Lead Time variation. With Changeover at 7 min, it has discovered a condition in which the system is robust vs. different buffer size and low Lead Time. With Changeover at 13 min it has found a higher Lead Time, but robust vs. Conditioned Maintenance variation.

Summarizing (Fig. 19), it could be got bigger Lead time but less variation if OEE is at 69% and Conditioned Maintenance at 15 min.

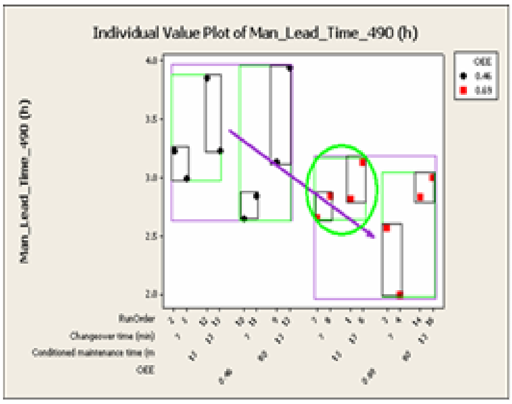


Fig. 19 Individual value plot

E. *Fill rate Variable*

No special indications are coming from practical view of the data. Then mining the dataset with raw, rank and Box-Cox power transformation, the following key signals were kept, showing only Main effects (Fig. 20).

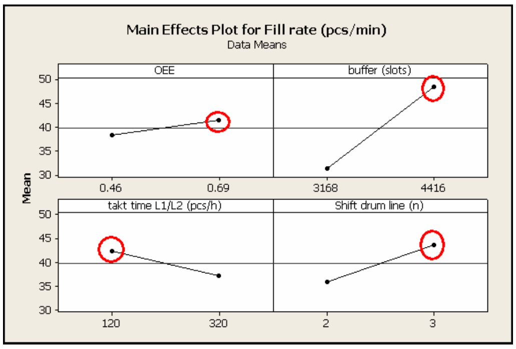


Fig. 20 Main Effects plot

To increase the Fill rate it should be worked on both Main Effects and Interactions, come out of the analysis because all of them are matching predictions: active factors have been found. In terms of Main Effects: Having higher OEE at 69%; Buffer with 4416 slots; Takt towards the lower level; Shift drum line with 3 shifts. Interactions: to increase the Fill Rate it's needed to move towards 3 shifts with which it could got a variation reduction vs. Takt Time variation; to increase the Fill Rate, it is need to work with bigger buffer (4416 slots); but with 3168 slots the system is independent from the OEE that is reasonable. Overall summarization is in the following plot (Fig. 21).

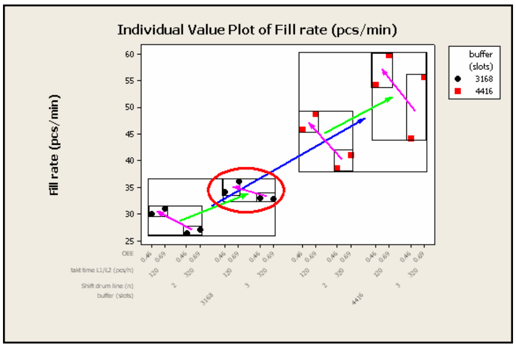


Fig. 21 Individual value plot

To reduce variation of the production in terms of Fill Rate, it is needed to work with a smaller buffer and with 3 Shifts. But this would mean that a reduced *Fill Rate* should be accepted. Direction to see an increase in the Fill rate is to work with bigger buffer and with 3 shifts.

From the results that have been shown, the directions related on how to manage production in order to increase *Parti Processate* and reduce WIP (mainly), are confirmed from DOE1 to DOE2. Above all it has been noticed that there is a clear path related to the sizing of the supermarket toward having more than 4000 slots available (4416 currently tested). This buffer size would enable the Manufacturing to manage also critical situation in which OEE is really at low level (less than 50%) and operations could be in *full emergency mode*.

VII. Third Stage of the Investigation (DOE3)

After having discussed study results with Industrial Engineering Dept Managers and Supervisors, as well as with Manufacturing Staff, even though they agreed about results and about the "theoretical" size of the drum supermarket, some space availability constraints were evident in the area where the buffer should be installed. Due to those constraints it was decided to run another sequential DOE (DOE3), to take into account the relevant physical issues. The simulation model was not changed, but it was decided to work according to Factory Management indications with 3 shifts and looking at only 490 washing machine platform that is the Naples Factory production mission. The investigating operations were related to the max size Supermarket implementing: 3700 drums. This was in line with what discovered with the previous simulations. But a check about what could have happened and what could be limitations or critical aspects was considered important. Because the main directions were clear, a FF DOE with 3 factors on 8 runs was considered enough to check potential criticalities and bottlenecks. The focus was only on WIP and Lead Time of 490 models. Let's take a look at the planning phase.

Factor	(-1)	(+1)	Predicted Best level	Predicted Importance (H - M- L)	Theories
OEE	46%	69%	69%	H	Better overall process perfomances with higher OEE. 69% of OEE is calculated based upon 0.94 of availability, 0.97 of quality and 0.76 of Performance (AxPxQ); 46% of OEE is got with P=0.5.
buffer	3168	3700	3700	H	Indications of the previous DOE say that we have to work towards 4416 buffer size.
takt time L1/L2	120 pieces/hour (30")	320 pieces/hour (11.25")	320 pieces/hour	H	Indications from previous DOE and common sense say more parts processed and less waiting time when lower takt time.

Fig. 22 Prediction Table

After Pareto and Residual analysis of raw and ranked data, the following key signals came out (Fig 23):

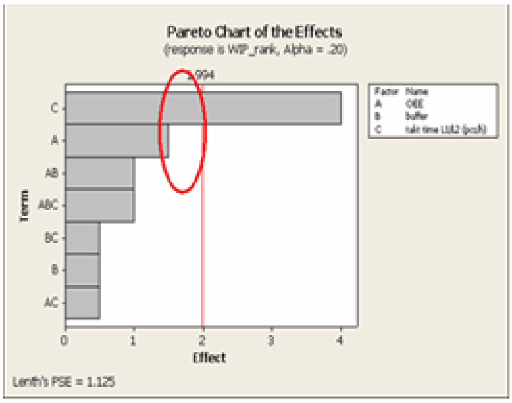


Fig. 23 Pareto plot

To reduce WIP OEE should be increased and at the same time the reduction of the takt time (more pcs/h) is needed. Everything matched predictions. Even though not statistical significant and not so near to borderline, it would be interesting to investigate OEE*buffer on the WIP (Fig. 24).

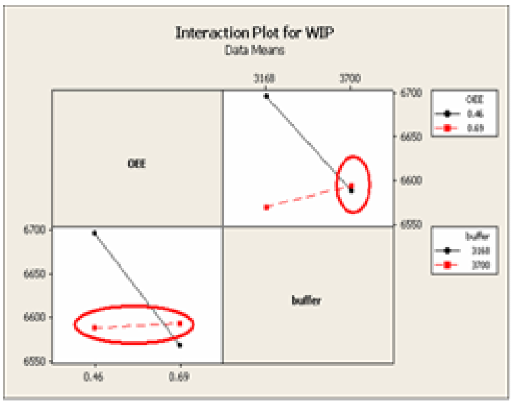


Fig. 24 Interaction plot

It could be seen that working on buffer at 3700 slots we are robust to the OEE variation, keeping the control on WIP. Statistical significance is only used as suggestion: engineering is the key driver for the process changes solutions.

A. *Manufacturing Lead Time_490 Variable*

In this case, because there is no clear signal from the practical analysis, it could be jumped directly to Pareto and Residual analysis, keeping the key signals (fig 25-1, 25-2):

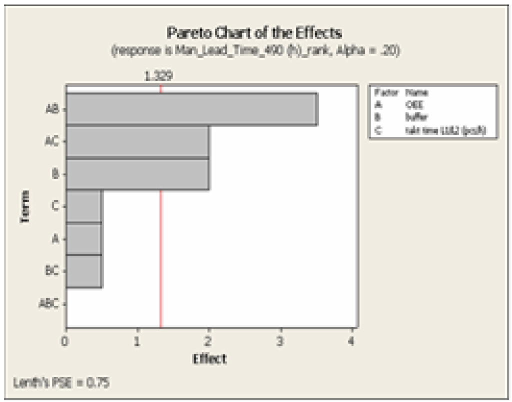


Fig. 25-1 Pareto plot

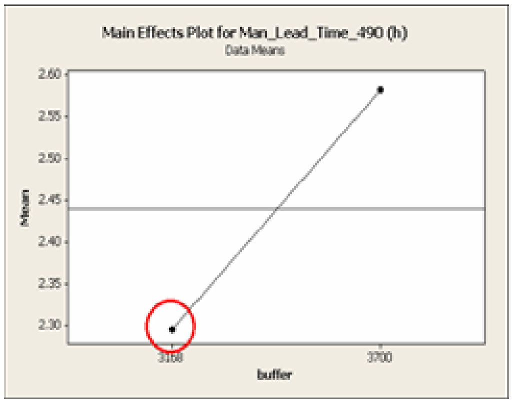


Fig. 25-2 Main Effects plot

To reduce Manufacturing Lead time it is needed to work with a reduced buffer in terms of Main effects.

In terms of interactions, it can be noticed that with lower OEE, Manufacturing Lead Time can be can managed, keeping variation lower and reducing the mean if the buffer is at 3700 (compared with buffer at 3168 parts). It can be said that Manufacturing Lead time can be reduced with OEE at 69%. With reduced OEE, the takt time should be reduced as well, hence reducing the pcs/h., setting knobs at 120pcs/h. At 69% OEE, Manufacturing Lead Time variation can be kept lower (Fig. 26).

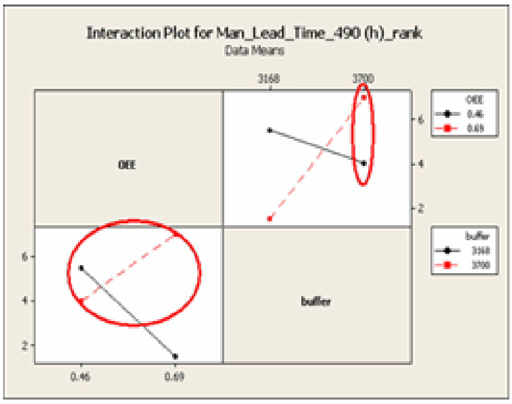


Fig. 26 Interaction plots

The most interesting aspect is that even a lower OEE occurs production could be managed avoiding doing useless stocks, with 3700 slot buffer.

Summarizing, we got the following indications about directions where to work (Fig. 27).

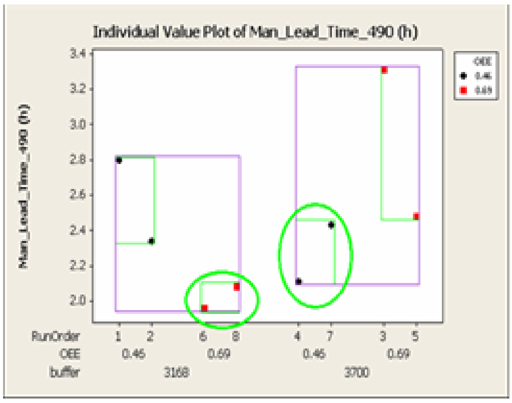


Fig. 27 Individual value plot

VIII. Results and Conclusion

Designed experimentation helped to reduce the time to acquire the needed engineering knowledge, supporting manufacturing process choices, driving the money investment in sizing the supermarket, avoiding expensive adjustments, when the buffer would have been already installed (when it could be too late). Key take away coming from model are becoming more reliable and near to the real life, as the new knowledge acquired helped to refine the model itself, coming out with a simulated system with which it was possible to force bad working conditions (e.g. downtime, long stops, accounted with low OEE). By the way it should be highlighted that signals coming from the simulation are limited by the current process knowledge that is somehow based on the data currently collection done on the real process and on expertise of the supervisors and operators of the manufacturing. The simulation model has been based on the data coming from previous study and continuous data sampling carried out in the daily job, but because “*All models are wrong and some are useful*” (G.E.P. Box), indications should be used as suggestions and support to decisions and of course need to be checked in practice. In terms of experimentation approach, OpEx approach typically starts looking at direction with High Fractionated Experimentation in order to optimize time and resources compared with the gained knowledge. Full Factorials are used only at the end of the experimentation, in order to map the response surface around the optimum, when directions are clear. Here it seems that somehow we moved against this flow, because we started with a Full Factorial DOE. In reality this is not true, because when the experimentation started, the simulation model was at the very beginning and we did not know what type of useful results we could gain “playing” with a lot of variables and putting efforts in the planning phase. The first DOE was useful to start to understand if the model worked in the sense of giving feedbacks of any practical meaning. Then, after having seen that things were working correctly, it was decide to improve the model itself and to start the typical direction searching of our approach. By the way, we decided to keep the early study steps as a part of our learning cycle.

At the end, the study helped to define the supermarket size (3700 pcs) and a lot of potential hints to be followed in case of critical situations. Arena simulation (features of the SW allowed us to inject Random Noise in the experimentation and to run a Statistical Significance Assessment thru’ Pareto analysis) demonstrated all its good points, high level of flexibility and potentialities in terms of simulating Manufacturing line scenarios that joint together with the Cause and Effect thinking, got with designed experimentation, brought to a great support system to decisions. DOE’s in simulation environment is a good practice that should be applied at the beginning of each investigation process in order to familiarize with whatever system (process or product) in order to reproduce potential scenarios and failure modes.

References

[1] 2001. Cudney, E.A. and J. Fargher. *Using Standard Work in Lean Manufacturing*, IIE Annual Conference.

[2] 2002. Van Goubergen, D. and H. Van Landeghem. *Reducing Setup Times of Manufacturing Lines*, International Conference on Flexible Automation and Intelligent Manufacturing, Dresden.

[3] 2000. Henderson, B.A. and J. L. Larco, *Lean Transformation: How to Change Your Business into a Lean Enterprise*, The Oaklea Press.

[4] 1997. Van Landeghem, H. and M. Debuf., *Supply Chain Characterization through Monte Carlo Simulation*, Proceedings of the Production Economics Conference, Goteborg.

[5] 1998. Van Landeghem, H., *Experiments with MISTRAL, a Supply Chain Simulator*, Proceedings of International Workshop, Riga.

[6] 2001. Whitman, L., R. Underdown, and M. Deese, *A Physical Demonstration of Lean Concepts*, IIE Annual Conference.

[7] 1996. Wendy Bergerud, *Displaying Factor Relationships in Experiments*, The American Statistician, Vol. 50, 1996.

[8] 1991. Moen, Ronald, Nolan, Thomas, Provost, Lloyd, *Improving Quality through Planned Experimentation*, McGraw Hill (ISBN 0-07-042673-2).

[9] 1995. W. Ross, D. Sanders, T. Cooper, *Six Sigma Associates Copyright 1995*, All Rights Reserved.

[10] 1978. Box, George, Hunter, William, and Hunter, J. Stuart, *Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building*, Wiley (ISBN 0-471-09315-7).

[11] 1987. Box, George E. P., and Bisgaard, S.*, The Scientific Context of Quality Improvement*, Quality Progress.

[12] V. A. Torres, *A simple analysis of Unreplicated Factorials with Possible Abnormalities*, Journal of Quality Technology, Vol. 25, No. 3.

[13] 2005. P. G. Mathews, *Design of Experiments with MINITAB*, printed by ASQ Quality Press 2005.

[14] 1991. G.E.P. Box, *George's Column: Finding Bad Values in Factorial Designs* Quality Engineering, Marcel Dekker Inc. -1991.

[15] 1976. Daniel, Cuthbert, *Applications of Statistics to Industrial Experiments* Wiley (ISBN 0-471-19469-7).

[16] 1991. Montgomery, Douglas C., *Design and Analysis of Experiments*, Wiley (ISBN 0-471-52000-4).

[17] 2000. D. Sanders and J. Coleman, *Considerations Associated with Restrictions on Randomization In Industrial Experimentation*, Published Quality Engineering 1999-2000 12(1) pp. 57-64.

[18] 2008. E. Romano, L.C. Santillo, P. Zoppoli, *The change from push to pull production: effects analysis and simulation*, Proceedings of the WSEAS International Conferences, Santander – Cantabria (SPAIN), September 23-25 – 2008 (ISBN 978-960-6766-55-8).

[19] Whirlpool Proprietary Information.

[20] 1991. G.E.P. Box, *George's Column: "Sequential Experimentation and Sequential Assembly of Design"* Quality Engineering (Marcel Dekker Inc. -1992).

[21] 2004. P. Bayle, M. Farrington, B. Sharp, C. Hild and D. Sanders, *Illustration of Six Sigma* Assistance on a Design Project Quality Engineering*, Marcel Dekker Inc. -2001.

[22] 2007. P.Yol Jang, *Evolution Structure of a Process and Resource Models-based Simulation for the Supply Chain Management*, Proceedings of the 11th WSEAS International Conference on APPLIED MATHEMATICS, Dallas, Texas, USA, March 22-24, 2007.

[23] 2008. Sangwan KIM, Kang Dong Won, Lee Joon Kyung, Jeong You Hyeon, *Simulation results for calculating the number of requirement NGN systems in case of merging PSTN into NGN and Suggestion of NGN merging strategy*, 12th WSEAS International Conference on COMMUNICATIONS, Heraklion, Greece, July 23-25, 2008. ISSN: 1790-5117. ISBN: 978-960-6766-84-8.

[24] 2007. A. Teilans, Y. Merkuryev and A. Grinbergs, *Simulation of UML models using ARENA*, 6th WSEAS International Conference on SYSTEM SCIENCE and SIMULATION in ENGINEERING, Venice, Italy, November 21-23, 2007.

[25] 2008. F. N. Koumboulis, M. P. Tzamtzi, M. G. Skarpetis*, A Decision Support System for Safe Switching Control -Design and Implementation*, WSEAS TRANSACTIONS on SYSTEMS and CONTROL. Issue 11, Volume 3, November 2008. ISSN: 1991-8763.

[26] 2004. R.C. Berredo, L.N. Canha, P.Ya. Ekel,L.C.A. Ferreira and M.V.C. Maciel, *Experimental Design and Models of Power System Optimization and Control*, WSEAS TRANSACTIONS on SYSTEMS and CONTROL. Issue 1, Volume 3, January 2008. ISSN: 1991-8763.