Using Nested Simulation for Evaluating Next Period Workload Anticipation Capability of a Control System

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Abstract
Simulation is a powerful tool able to anticipate the behavior of complex systems; often this ability is used for on-line control strategy in several industrial and civil applications. Models are currently used for supporting next period workload in gas dispatching networks as well as in electrical power generation management. In the process industry (i.e. steel making plants) simulation is the base technique for ensuring proper appointment among different processes (i.e. Ladle Furnaces and Continuous Casting); in maritime logistics several applications have been proposed for container yard planning and for mooring optimization. Moreover in the manufacturing sector several applications of Scheduling and Simulating systems are well known. In all such applications on-line simulation has been extensively used for supporting operative decision making. In the proposed application a department store is here controlled by an on-line simulator devoted to investigate the impact of counter's management policy. In the common practice, in fact, a fixed number of people is used both for counter's staffing and for shelves replenishment. Opening a counter, generally speaking, will divert a worker from shelf replenishment in favor of a reduction in the customer's average time spent in queue, resulting a temporary increase in the stock out risk. The effect of such behavior is delayed and a consequent oscillating path will emerge affecting seriously the performances of a real life department store. The paper presents a reflective simulation model able to simulate such system with an embedded simulator in order to investigate the expected performances of such simulation-in-the-loop control model. Methodology and case study are presented and discussed.

Keywords: Nested Simulation, Simula, Anticipation, Staff Scheduling, Risk Management.

1. Introduction

Simulation has proven to be very effective in supporting schedule evaluation for complex systems in several industrial applications. In distribution logistics industry there is a clear relation between picking reduction time and profitability. The more the picking and kitting times are reduced the more orders can be accomplished in one shift, resulting in an increase of the profitability rate. In the past, the staff scheduling required for assigning picking tasks to operators was executed at the beginning of the shift while today a continuous rescheduling activity has to be made in order to increase the response readiness to meet the replenishment take times.

The problem is not even a matter of scheduling performance, since a schedule will never be respected; it is more a matter of robustness of the planning. In such scenario simulation can play a crucial role since it offers the possibility of quantitatively evaluate a planning performance when the original planning scenario has changed. This simulation-in-the-loop decision making process can be effectively evaluated by simulating a decision support system that has simulation in its internal logic: this is the case of the proposed reflective simulation model. A first example can be derived from a real life application in the steel manufacturing industry where the tight production scheme requires a punctual respect of the various process appointments. A second example regards the scheduling of tellers in a supermarket through an "anticipatory" simulation model.

2. A First Example: the Steel Industry

In the following a brief description of the steel process is presented. Scrap metal is delivered to a scrap bay, located next to the melt shop. Scrap generally comes in two main grades: shred (scrap light enough to have been passed through a shredder) and heavy melt (large slabs and beams), along with some direct reduced iron (DRI) or pig iron for chemical balance. The scrap is loaded into large buckets called baskets, with 'clamshell' doors for a base. Care is taken to layer the scrap in the basket to ensure good furnace operation; heavy melt is placed on top of a light layer of protective shred, on top of which is placed more shred. These layers should be present in the furnace after charging. After loading, the basket may pass to a scrap pre-heater, which uses hot furnace off-gases to heat the scrap and recover energy to increase plant overall efficiency.

The scrap basket is then taken to the melt shop, the roof is swung off the furnace, which is charged with scrap from the basket. Charging is one of the most dangerous operation for the EAF operators. There is a lot of energy generated by multiple tons of falling metal; any liquid metal in the furnace is often displaced upwards and outwards by the solid scrap, and the grease and dust that coat the scrap are ignited if the furnace is hot, resulting in a fireball erupting out of the top of the furnace and the slag door. In some twin-shell furnaces, the scrap is charged into the second shell while the first is being melted down, and pre-heated with off-gas from the active shell. Other operations are continuous charging - pre-heating scrap on a conveyor belt, which then discharges the scrap into the proper furnace, or charging the scrap from a shaft set above the furnace with off-gases directed through the shaft. Yet other furnaces can be charged with hot (molten) metal from other operations.

After charging, the roof is swung back over the furnace and the meltdown commences. The electrodes are lowered onto the scrap, an arc is struck and the electrodes are then set to bore into the layer of shred at the top of the furnace. Lower voltages are selected for this first part of the operation to protect the roof and walls from excessive heat and damage from the arcs. Once the electrodes have reached the heavy melt at the base of the furnace and the arcs are shielded by the scrap, the voltage can be increased and the electrodes raised slightly, lengthening the arcs and increasing power to the melt. This enables a molten pool to form more rapidly, reducing tap-to-tap times. In more modern furnaces, oxygen is also lanced into the scrap, combusting or cutting the steel and burning out carbon, and sometimes chemical heat is provided by wall-mounted oxy-fuel burners. Both processes accelerate scrap meltdown.

An important part of steelmaking is the formation of slag, which floats on the surface of the molten steel. Slag usually consists of metal oxides, and acts as a destination for oxidized impurities, as a thermal blanket (stopping excessive heat loss) and helping to reduce erosion of the refractory lining. For a furnace with basic refractories, which includes most carbon steel-producing furnaces, the usual slag formers are calcium oxide (CaO, in the form of burnt lime) and magnesium oxide (MgO, in the form of dolomite and magnesite). These slag formers are either charged with the scrap, or blown into the furnace during meltdown. Later in the heat, carbon (in the form of coke) is lanced into this slag layer, partially combusting to form carbon monoxide gas, which then causes the slag to foam, allowing greater thermal efficiency and better arc stability and electrical efficiency. The slag blanket also covers the arcs, prevents damage to the furnace roof and sidewalls from radiant heat.

Once flat bath conditions are reached, i.e. the scrap has been completely melted down, often another bucket of scrap is charged into the furnace and melted down. After the second charge is completely melted, refining operations take place to check and correct the steel chemistry and superheat the melt above its freezing temperature in preparation for tapping. More slag formers are introduced and more oxygen is lanced into the bath, burning out impurities such as silicon, sulfur, phosphorus, aluminum, manganese and calcium and removing their oxides to the slag. Metals that have a poorer affinity for oxygen than iron, such as nickel and copper, cannot be removed through oxidation and must be controlled through scrap chemistry alone, such as introducing the direct reduced iron and pig iron mentioned earlier. A foaming slag is maintained throughout, and often overflows the furnace to pour out of the slag door into the slag pit. Temperature sampling and chemical sampling (in the form of a 'chill' - a small, solidified sample of the steel) take place via automatic lances.

Once the temperature and chemistry are correct, the steel is tapped out into a preheated ladle through tilting the furnace. As soon as slag is detected during tapping, the furnace is rapidly tilted back towards the de-slagging side, minimizing slag entering the ladle. During tapping some alloy additions are introduced into the metal stream. Often, few tons of liquid steel and slag are left in the furnace in order to form a 'hot heel', which helps preheating the next charge of scrap and accelerating its meltdown. During and after tapping, the furnace is 'turned around': the slag door is cleaned of solidified slag, repairs may take place, and electrodes are inspected for damage or lengthened through the addition of new segments; the taphole is filled with sand at the completion of tapping. For a 90-tonne, medium-power furnace, the whole process will usually take about 60-70 minutes from the tapping of one heat to the tapping of the next (the tap-to-tap time).

3. Critical Issues that Require On-line Simulation

A crucial part in the steel manufacturing process is represented by the internal transportation: there is the need to move hundreds of tons of liquid steel (at approx 1500° C) that should be treated in Ladle Furnace and subsequently in Vacuum Degassing before the temperature drops. Sometimes a few hundreds of temperature loss make the steel unsuitable for the following Continuous Casting Operations (CCO). The internal movement are generally made by specialized EOT Cranes (Electrical Operated Transfer Crane) sharing the same bay. This is the tricky part of the problem, EOT Cranes, in usual industrial applications, operate one per bay avoiding collision problems; in steel making industry is usual to have more than one EOT Crane in the same bay (some facilities have more than 4 EOT Crane on the same bay). This situation needs continuous monitoring of the position and speed of each Crane increasing the complexity of the system and reducing its transporting potentials. During transportation, in fact, it will be necessary to move other EOT Cranes on the same bay in order to avoid collisions and operate in safe conditions. Figure 1presents a classical situation in which, due to poor layout design, several movements should be performed at the same time in the same bay (CPF). As it is possible to notice, there are two main flows coexisting at the same time: the full ladle cycle, centrifugal, that flows from Electrical Furnace (COV in the figure) to CCO, and the empty ladle cycle, centripetal, that returns back from CCO to COV via the ladle maintenance stations. Since several crossings are noticeable in figure 1, it is possible to imagine that this scenario will create a considerable congestions and heavy delays in transportation (leading temperature to drop and poor steel quality).

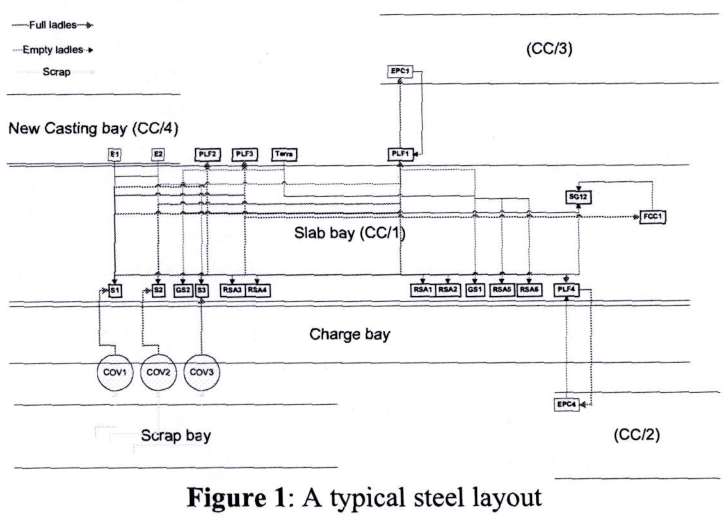

Figure 1: A typical steel layout

There are several emerging considerations that arise from the analysis of the proposed situation:

- slab Bay is extremely affected (60 different kind of missions);
- traffic causes delay and increases the complexity;

- delays affect production planning, requiring continuous adjustment from CFA Office (requires 2nd level modeling);
- at full speed all CCOs have a tighten schedule reducing the possibility of compensation and delay recovery;
- increasing the production is possible only by reducing delays in the CPF Bay;
- this is mainly related to the possibility of "anticipate" the right moment for creating a EOT Crane mission (definitely, we need simulation).

The effect of "anticipate" the right moment is evident in Figure 2 and 3. Figure 2 is related to a "blind" system that simply orders an EOT Crane as soon as the items need to be forwarded to a new position. The green line is the optimal moving time (theoretical); the blue squares are the actual (simulated values). As it is possible to notice, for an expected 3 minutes mission often a 20 minutes mission is required. Figure 3 presents the same situation but the EOT Crane mission is created according to an "anticipated" vision of the system future situation. The advantage is evident.

In such scenario simulation can play a crucial role since it offers the possibility of quantitatively evaluating a planning performance when the original planning scenario has changed.

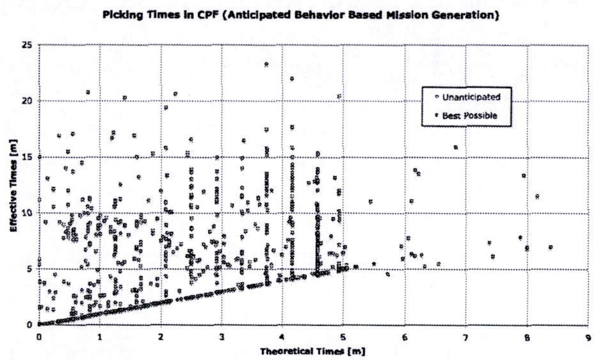

Figure 2: Picking times versus theoretical times in a blind system

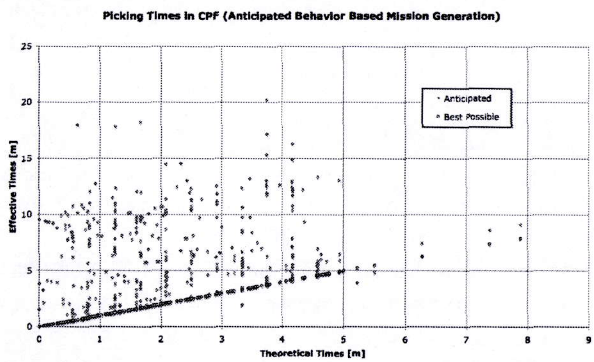

Figure 3: Picking times versus theoretical times in a "anticipated" system

4. Quasi Black Box Modeling in the Supermarket Context

There is a wide class of phenomena involving intelligent agents (i.e. customer behavior in a shop, drivers at a toll plaza) that can be accurately modeled only by having an exact knowledge of the internal agent's behavior. Such knowledge can be obtained at the price of long data collection campaign, multiple agent tracing, social behavior modeling and many other time-consuming techniques.

In the supermarket distribution industry, there is a growing interest in the possibility of accurately modeling the customer behavior in order to optimize the number of tellers to be opened in each period or the best way to use workers for shelves replenishment. In a supermarket, in fact, a stock out event is generally associated with a potential lost sale whose criticality is proportional to the duration of the stock out and the number of the items involved.

Another important issue is related to the average time spent by a single customer into the shop; it is not a secret that long waiting time in the teller queue seriously affects the profitability of the shop. This point is becoming more important in some countries, like Italy, where a significant portion of the fresh product is sold by operators inside a special area of the supermarket. In Italy, in fact, customer perception of the quality of the same raw ham pre-packed in self-service or sliced at-the-moment could be dramatically different, resulting in a consistent sale loss in the short term and a consequent customer loss in the medium term for a only self service supermarket. In the recent years, several techniques have been used to trace customer behavior into shops ranging from RFID tag on the trolley up to dedicated scanning cameras placed at selected points of the shops. The results were generally poor, since the natural variability of the process drives very quickly the observation out of control.

Another important issue is related to external driven variability: in bad weather days the number of customers spending their off-duty afternoon in a supermarket or department store increase dramatically, so there is a great interest in supermarket industry in forecasting queue length and customers' waiting times according to the weather change.

Since many agent-based simulation projects failed in the past for the lack of credible data in the customer behavior modeling, a different approach should be used.

In the proposed approach we abandoned the agent based behavior-modeling chimera in favor of a quasi-black box approach where some parameters can be actively measured and used for an input/output model.

In real life application a supermarket can be summarized as a black box where customers enter at the entrance gate, spend some time in purchasing – according to their internal needs – and go to the tellers for paying.

While it is quite simple to measure the input rate, it is very hard to investigate the single entity choice. Other important measures that can be conducted on supermarkets are: the post teller output rate and the check composition. While the first is only a mediated measure of the teller efficiency, the second could be used for obtaining an impressive list of information such as the estimation of the average time spent in purchasing and/or in internal queues.

At this point a quasi-black box simulator can be used during regular operating hours to investigate the present system for possible evolutions and to choose the best performing tactics. Because of the continuous updating of the simulator, an evolving scenario can be easily accommodated.

5. Reflective Simulation Using SIMULA: a Supermarket Application

The use of on-line simulation for supporting complex decision making in evolving scenario has been widely documented in several industrial applications; however the great part of those was mainly related to manufacturing industry where the extensive use of automation transformed the data collection into a matter of software integration. In supermarket industry, it is simply impossible to track customer behavior without high costs and without violating the privacy protection act.

It is not possible to study the customer purchasing behavior at the entity level so it is very difficult to implement an agent based simulation to support the tellers opening schedule. On the other side the use of the quasi-black box simulation methodology requires a credible validation in order to be fine-tuned and adopted into a real life application. The need of a test bed for the quasi-black box methodology requires the adoption of a model able to reproduce an internal simulation and its decision making process while simulating normal operation procedures and scenario evolution.

The authors have addressed this issue with the use of the nested simulation where the outer model will be used to simulate the real world and the nested simulation will be used to act as the on-line simulator and its consequent Decision Making Process. In the proposed application a simple supermarket model is modeled in the outer simulator; the customers arriving process is modeled by using a uniform distribution of the mean time between arrivals. A multiple period simulation exercise is used to simulate up to 9 different customer arriving rates during a single day. In this way a possible perturbation path can be actively modeled by continuously adjusting the arriving rate.

In the same simulator a nested simulation is implemented using the same logic but obtaining its distribution data from statistics of the outer simulator. Practically the inner simulator can obtain the customer arriving ratio and the customer mean processing time from a sample made in the “Real World”. Like in reality, the simulator can only investigate the possible evolution of the “Real World” from the incomplete samples “visible” in different points.

In other words only the Arriving process and the Leaving Supermarket process are visible and all the other information can only be guessed, particularly the customers’ Inter Arrival Time (IAT) statistics is collected by a sensor placed near the entrance door. In this way the inner simulation has the visibility on the real world similar to the one that it will have in the real application.

During the simulation of the “Real World”, the user will be prompted for a choice made on the possible scenario evolution computed from the present point and according to a predefined teller opening scheme. This fact leads to multiple time axes departing from the “Real” to the various “Virtual” worlds. Since internal statistics are continuously updated the inner simulation can be used to investigate the possible reaction to an evolving scenario.

The nested simulation model can now be applied to the quasi-black box methodology to test the effectiveness of the approach.

Among the various tools and languages suitable for simulation applications, the authors decided to implement the technological demonstrator using SIMULA, a general-purpose language with a specific capability for nested simulation. This choice was driven following the literature that indicate in SIMULA and in Java (Kindler et al. 1997) the two languages capable of supporting complex exercises in nested simulation.

Life rules of Simula objects are coroutines which may be temporarily stopped and later resumed. There are two levels of (quasi)parallelism in Simula. The first level does not work with time and the programmer "thinks in quasiparallel". The second level introduces the notion of time; the programmer works with parallel processes. The first level can be applied to all classes, while the second one is implemented by the class "Process" of the system class Simulation. A quasiparallel system (QPS) in Simula is basically a block whose body creates some objects that together with the main block made up the system of quasiparallel coroutines. Because Simula (unlike for example Pascal) is a true block oriented language, a block (that generally means a QPS) can occur at any place in the code as a statement. It means that a QPS can contain local (nested) QPS's that can also contain local QPS's leading a complex structure of nested quasiparallel process. SIMULA is today available and supported in several commercial implementations; however the authors decided to use GNU Cim version 3.36. GNU Cim is a compiler for the programming language SIMULA (except unspecified parameters to formal or virtual procedures). It offers a class concept, separate compilation with full type checking, interface to external C routines, an application package for process simulation and a coroutine concept.

GNU Cim is a SIMULA compiler whose portability is based on the C programming language. The compiler and the run-time system is written in C, and the compiler produces C code, that is passed to a C compiler for further processing towards machine code. GNU Cim is copyrighted by Sverre Hvammen Johansen, Stein Krogdahl, and Terje Mjs, Department of Informatics, University of Oslo.

In the implemented simulation model the customer enters into the store and is "seen" by the entrance sensor providing a simple statistics for the Inner Customer Generator Model (Sklenar, 1997). The customer has the chance to spend some time purchasing in the store in the self-service area (free service shelves) and, eventually, purchase some butchery or bakery products at the serviced desk. Butcher and bakery area are served by 12 clerks that maintain a separate queue for their services. An average 40% of the customers will require products from the butcher or bakery, resulting in a delay in their purchasing process. At the end of the purchasing process the customer will go to the counter for the check out, as first choice the shortest teller queue will be chosen. Since the time spent in queue is usually a critical factor in the store management, a simple algorithm will implement the behavior of queue switching which is usually followed by the typical Italian customer.

While queuing for a teller, the customer will "look around" in the adjacent queues investigating for a shorter one. In case of an adjacent queue has two people less than the present he will jump in the shorter queue in order to save time. Jumping is not allowed into a closing queue.

If a queue is approaching closing, no more customers will be accepted in entrance and the counter will terminate its duties after the last customer in queue. An opening teller will generally cause queue switching in its first minutes of operating time.

The number of active tellers is defined at the beginning of the 12 simulation periods; customers eventually left in the shop at the end of a simulation will be served before closing. The outer simulator collects statistics on the arriving customers (minimum and maximum inter arrival time) and use it for the internal simulation.

At each simulated step the user was prompted for the opening teller choice, with the results of the simulation made in the "Virtual World" and immediately informed about the result of the simulation in the "Real World". The use of SIMULA poses some difficulties in Verification & Validation; such language, in fact, lacks the modern tool features for rapid GUI development; this is becoming very critical when compared to Arena™, Simul8™, ProModel™ tools that have nice tool for supporting simulation visualization.

In order to avoid this problem, authors used Wolverine Proof Animation™ that supports very high-fidelity visualization for general purpose simulation language. Proof Animation™ provides both off-line and on-line animation on Windows platforms and can be used by a wide variety of programs.

The implemented model introduced an internal Fresh Product shop inside the supermarket area; now customers have the chance to buy some fresh products directly in the Department Store and are served by a 4-server position that generates an internal queue system.

Again the internal simulation, representing the "Virtual World", is driven by statistics generated by the outer simulation model, representing the "Real World". Control points of this new model are the customer arrival, obtained at the customer's entrance metering system, and the total percentage of customers spending their time into the Fresh Product Store (Butchery/Bakery) obtained with the customer check analysis.

6. An Application to a Real Supermarket Case

The here proposed application was tested with a complete implementation including a Fresh Product internal store, 15 tellers rows and a queue-balancing algorithm.

The simulator provides a 12 hour period covering the typical opening hours of an Italian Supermarket (8AM-8PM), typical peaks hour occur at 10 AM and 5 PM. Since the model was created to work also with a more complex time path (in order to be used later on another research) the generation of the load curve was embedded into the outer model itself using equation (1).

$$\lambda = 10 \cdot \left\{ \left(\frac{1}{2\sqrt{2\pi}} e^{-\frac{k+7-p_1}{2\sqrt{2}}} + \frac{1}{2\sqrt{2\pi}} e^{-\frac{k+7-p_2}{2\sqrt{2}}} \right) \cdot \left[1.5 + \frac{1}{19} \cdot (19 - k + 1) \right] \right\} \quad (1)$$

where:

- λ: is the customer arrival rate, measured in customers' arrivals per minute;
- p_1: is the morning peak time;
- p_2: is the afternoon peak time;

This particular behavior (Figure 4) is able to introduce a level of complexity into the model. Since the internal simulation model is driven by external model statistics, one hour delay between increasing or decreasing IAT and internal model awareness is introduced as possible oscillating path (Banks 2000), this point has been discussed in (Bruzzone, Revetria, 1999) and can be properly addressed using artificial neural networks as Computing Anticipatory Model for the IAT time path (Bruzzone et al., 2001).

At the same time the implemented model can be used to investigate the benefits of innovative methodologies for products replenishments over the shelves, as discussed in (Bruzzone et al., 2001).

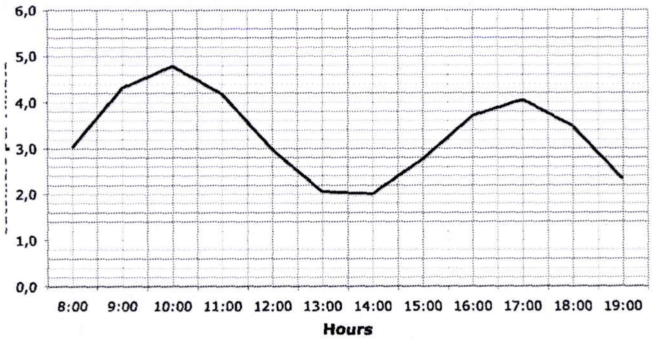

Figure 4: Customers arriving rate according to day time

The implemented model requires only a data collection for the teller process and the internal Fresh Product store; both internal (nested) and external (outer) simulation models works on the same statistics implementing a Standard Random Generator for the teller process and a Uniform Random Generator for the internal Fresh Product Store.

The internal simulation serves all the possible configurations from 1 to 15 opened tellers driving the possibility to investigate how many tellers keep opened in each of the 12 hours of the day shift.

Since there is no knowledge about the number of customers in queue at the end of each "Real World" hour, the internal simulator may start with a warm up period of 15 minutes. Investigations made with a complete vision of the queue from the internal simulation demonstrate that the effectiveness of this choice was widely proven. For a complete discussion of this point and a quantitative evaluation of the Mean Squared Pure Error, it is suggested to see Revetria et al., 2006.

For the experimentation phase, two models were implemented: the first has a negative exponential IAT distribution in the outer model and a uniform distribution in the inner model; this choice was able to demonstrate the applicability of the proposed methodology to a "maximum ignorance case"; the second model implements correctly a negative exponential distribution. In both cases the parameters of the distribution were extracted from statistics made on the outer simulation model as in a real life scenario where data collection is carried out on the real system. The first experimental results present a poor performance (Figure 5); the systems appear to be ineffective in controlling TIS output variable resulting in an increase of the queues and in a reduction of the total customers served.

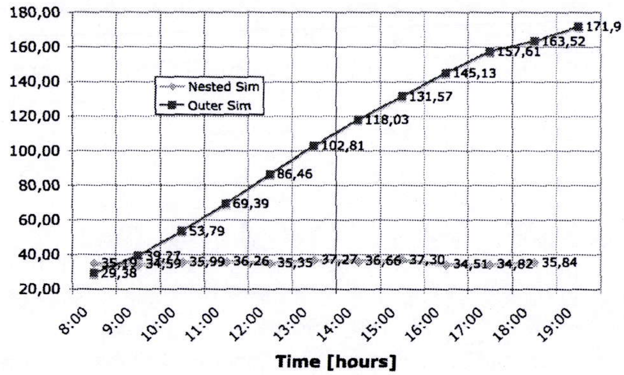

Figure 5: Poor performances of uniform model –divergent behavior

The simulation results for the second scenario are presented in Figure 6, showing a good capability of the system in controlling the TIS output variable also in the presence of an oscillating input behavior.

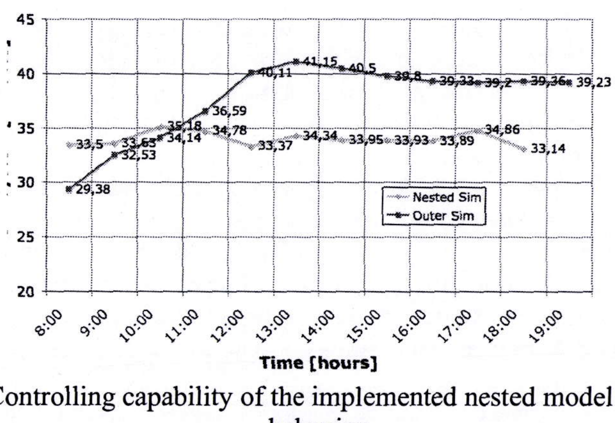

Figure 6: Controlling capability of the implemented nested model – convergent behavior

The proposed methodology presents some benefits also in terms of increasing the overall productivity of the supermarket; the first experiment, in fact, ended with only

1411 customers served in a 12 hours opening time frame against the 2217 obtained in the second experiment with a net increment of 57%.

7. Conclusions

The use of on-line simulation for controlling queue parameters and increase performances of a department store has proven to be very effective also the in case of application of a quasi-black box modeling paradigm.

Benefits can be studied well before implementation by using a nested simulation approach that is proper for this application domain. Among various simulation software SIMULA™, a 50-year-old language based on ALGOL™, is still in shape and is the right choice for a very effective implementation.

A practical application of the proposed methodology has been presented and discussed.

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