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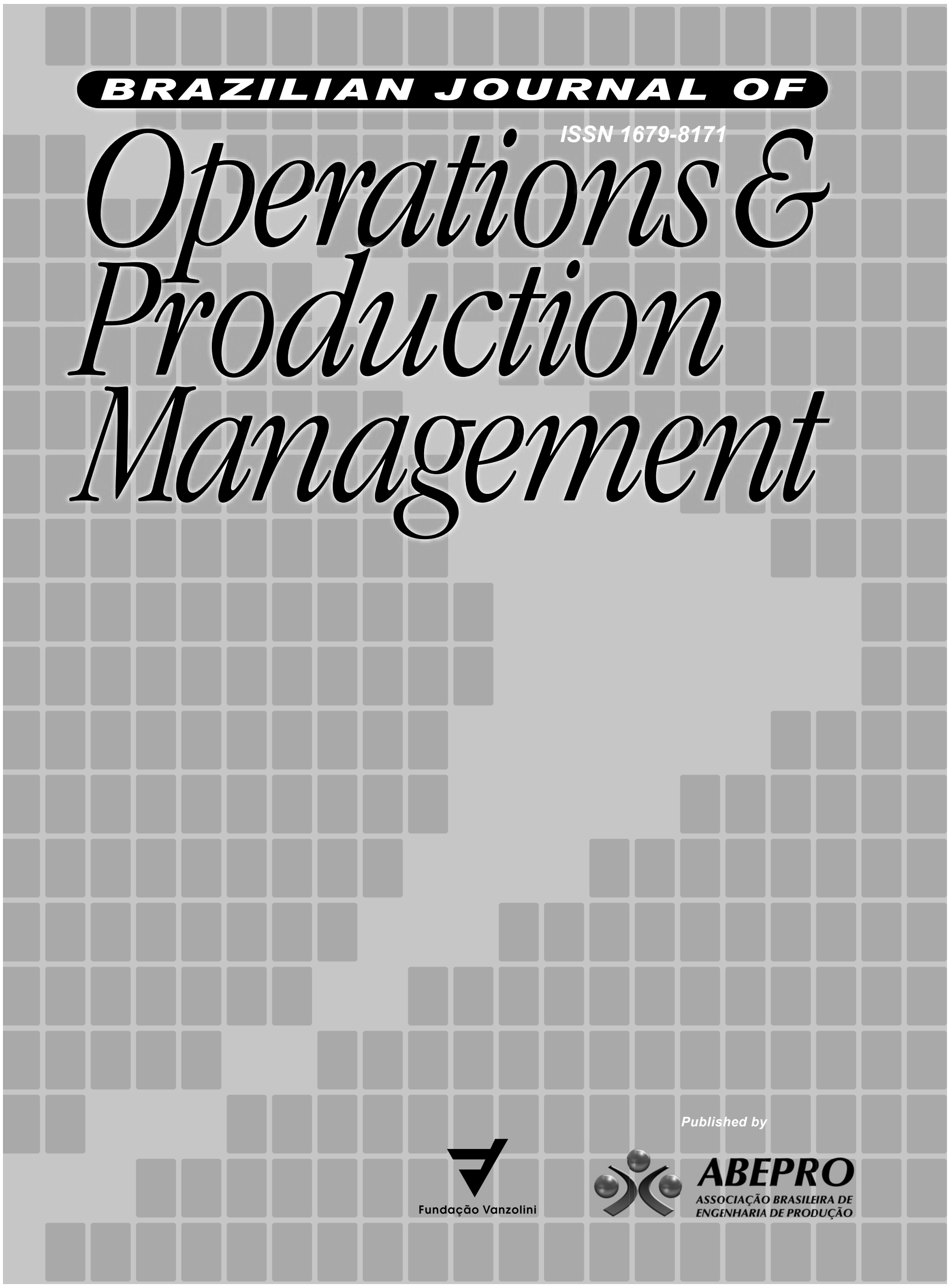


**Invited Editors:** Sérgio E. Gouvêa da Costa, Ricardo M. Naveiro and Guilherme E. Vieira

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# Editorial Introduction

This special issue of the Brazilian Journal of Operations and Production Management presents some of the best papers of the ICPR Americas 2006.

The third edition of the American International Conference on Production Research (ICPR) was held in Curitiba, Brazil, from July 30th thru August 2nd, 2006, and was organized by the Brazilian Association of Production Engineering (ABEPRO), and the Industrial & Systems Engineering Graduate Program (PPGEPS) of the Pontifical Catholic University of Paraná (PUCPR). It was an official Conference of the International Foundation for Production Research (IFPR).

There were about 200 papers submitted from Brazil, Argentina, Canada, Chile, Colombia, Costa Rica, England, France, Germany, Japan, Mexico, Portugal, Russia, Turkey and United States.

A double-blind review process selected approximately 100 papers for oral presentations (allocated in 5 Technical sessions) and 30 papers as posters. Among them, best ones were selected and the authors were invited to submit a more robust article. Then, these papers were double-blind reviewed and some of those that achieved the higher marks were selected to be part of this issue.

**In this Issue**

The first paper, by Eduardo R. Loures, Marco Busetti and Eduardo Portela (Pontifical Catholic University of Parana, Brazil, Brazil), deals with control-monitoring architectures for flexible manufacturing systems (FMS) based on Petri nets with objects (PNO), generating a framework based on a modular and hierarchic model structured in CMM modules. The second paper, by Adiel Teixeira de Almeida Filho, Fernando M. Campello de Souza and Adiel Teixeira de Almeida (Federal University of Pernambuco, Brazil, Brazil), presents a model based on multi criteria decision analysis that is a decision model that allows the implementation of the manufacturing strategy by the production function. The main issue in the paper is the aggregate planning. The following paper, by Luiz Bueno da Silva, Anand Subramanian, Fernanda Diniz de Sá and Francisco Soares Másculo (Federal University of Paraiba, Brazil), presents nonlinear models applied to studies in the ergonomics area, particularly the effect of the several variables (thermal perception, noise perception, age, and time of service) on the working ability. The sample was constituted of 60 public bus drivers. In the forth paper, by Jose F. Zamora (University of Costa Rica, Costa Rica), Raymundo Q. Forradellas (National University of Cuyo, Argentina) and Mauricio Camargo (National Polytechnic Institute of Lorraine, France), the authors present forecasting tools as an option to predict the product distribution and manufacturing needs and as a way to counterbalance the different negotiating force among actors. The last paper, by Dario Ikuo Miyake, Renato de Lima Sanctis and Felipe Salomão Banci (University of São Paulo, Brazil), presents an in-depth longitudinal case study of a consumer electric products manufacturer in Brazil that embarked on a program to migrate from the utilization of conveyor lines to the work-cell based assembly system in one of its plants.

This issue finalizes the presentation of the ICPR Americas 06 best papers. We expect to have brought relevant issues as well as innovative approaches in the research of production/industrial engineering and operations management communities.

Once again, we would like to thank ABEPRO Executive Board and the BJOPM Editorial Board for this opportunity.

This issue closes with ABEPRO's executive and ABEPRO's Editorial Board (NEA).

Sérgio E. Gouvêa da Costa, Ricardo M. Naveiro and Guilherme E. Vieira

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# A control-monitoring-maintenance framework based on Petri net with objects in flexible manufacturing system. Application to a robot-driven flexible cell.

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**Abstract**
The growing complexity of systems and the need for executing large projects have led to the development of complex flexible manufacturing systems (FMS) demanding specific control-monitoring architectures. The problem of failure occurrence tends to increase according to this complexity leading to time-consuming tasks as the localisation and repairing. The occurrence of failures during the exploitation stage can deeply modify the FMS performances or its availability. In this context, the maintenance integration into a control-monitoring system becomes an important issue, improving production time and minimizing unplanned costly breakdowns of FMS. We want to investigate the problem of triggering the maintenance, giving a useful decision support tool to evaluate the system availability since the control system's

early design stage. It also results in improvement of the system's functionality in terms of efficiency, productivity and quality. This paper proposes a control-monitoring-maintenance architecture (CMM) for FMS based on Petri nets with objects (PNO), where stochastic rates are associated to the modelling of maintenance planning. This framework is based on a modular and hierarchic model structured in CMM modules. The integration is based on a development methodology in which the maintenance aspects and policies are taken into account from the conception (modelling) stage. These efforts acts as a basis for the control architecture of a robot-driven flexible cell, connected to the Ethernet-TCP/IP.

**Keywords:** Flexible manufacturing system, Supervision, Maintenance, Petri Nets.

## INTRODUCTION

The flexible manufacturing system (FMS) can be considered as a system able to produce a wide variety of products under variable production conditions. Classically, this type of system is constituted by a set of elements and devices such as workstations, transport systems, programmable logic controllers, robots, and vision systems, connected to an industrial communication network. According to the manufacturing cell dimensions' increase, the control and supervision of its structure becomes more complex. Thus, to keep flexibility regarding its decision organization, a modular and hierarchic structure is proposed (Zamai *et al.*, 1997). Hierarchic architectures have been subject of many works during the last decades (Gershwin et al., 1988), (Giua & DiCesare, 1994), (Srinivasan & Jafari, 1993) and represent the framework basis of recent approaches concerning the control and monitoring of FMS (Jeng & Liang, 1998), (Pascal, 2000).

The demands for products with higher quality and competitive prices have led to the development of complex manufacturing systems. A consequence is that the number of failures tends to increase as well as the time required to locate and repair them. The occurrence of failures during nominal operation can deeply modify the FMS's performance or its availability. The improvement of production times and the minimisation of unplanned costly breakdowns of manufacturing systems becomes an important issue. The potential benefits of advanced manufacturing technologies (Gouvea *et al.*, 2000) to improve the strategic and competitive position of a firm have been shown to be closely sensitive to maintenance policies.

Maintenance and its integration with control and monitoring systems enable the improvement of systems functioning, regarding availability, efficiency, productivity and quality. Thus, it is possible to implement corrective and preventive actions, making repairs and servicing easier over the process elements, as well as a better control provision of tools and repair parts. In addition, integrated to a hierarchical supervision architecture it allows a better production scheduling and planning. Then, maintenance has to be planned and scheduled; planning the execution of maintenance tasks in accordance with a production plan. Thus, it is desirable that maintenance management studies be carried out from the system conception stage.

Different methods do not take maintenance into account as an isolated issue, but making it part of a supervision, control and monitoring system. Some works can be mentioned, such as the proposal of a maintenance model integrated into a supervision-control architecture performed by (Ly *et al.*, 2000), (Berruet, 1998), the maintenance and the reconfiguration aspects in (Tang & Zhou, 2001), and the modelling and management of maintenance policies proposed by (Simeu & Sassine, 2001), (Bondavalli & Filippini, 2004), (Mouss *et al.*, 2004), (Bérenguer *et al.*, 2004) by means of a stochastic Petri net and its extensions. Most of these approaches focus maintenance integrated into the monitoring systems in order to support the checking of resources and planning, where real time conditions are not pointed out. In (Jeng & Liang, 1998), a SMT (supervisor - monitor - trouble-shooters) framework presents an integrated design method for supervisory control, monitoring and troubleshooting, where real time aspects are considered.

Our approach looks into these two contexts (system conception stage and real time conditions in operation stage) through a CMM framework based on a development cycle methodology (DCM) proposed in (Loures & de Paula, 1999), (Santos *et al.*, 2004). The methodology consists of a cyclic three stages development – modelling, synthesis and implementation of the CMM structure. Maintenance aspects are also taken into account from the modelling stage (equipments indicators and maintenance policies rates) to the operating stage, where appropriate monitoring techniques feeds back the maintenance policies models triggered by the CMM structure. The proposed method is structured and modular. Following a classical top-down approach, it makes it possible to build simple models, which can be validated according the supervision level, and then interconnected in order to simulate the global system's behaviour.

One of the advantages of this approach is to consider the control - monitoring - maintenance functions simultaneously. Maintenance must be considered as one of the system's main functions, linked to the control and monitoring functions. The hierarchical and modular decomposition enables the implementation of maintenance policies, limiting its effects over the global system, allowing it to preserve its availability. Another advantage is the fact that, during maintenance actions, the monitoring is kept active and guarantees a coherent intervention in the process.

In this paper, the first section describes the control-monitoring architecture as a basic ground for the works. Then the integration of maintenance aspects is described, leading to the proposition of the CMM architecture. The next section presents an application of this architecture, which is under implementation in a real robot-driven flexible cell.

## CONTROL-MONITORING-MAINTENANCE ARCHITECTURE

The real time control of complex Discrete Events Systems (DES) is classically solved by structuring the control system, both hierarchical and modular, on a four-level decision organization: planning, real time scheduling/supervision, co-ordination and local control (Chaillet *et al.*, 1997). The control functioning principle in a hierarchic context requires that only the module that has emitted a request for the lower level is able to modify it (Zamai et al., 1997). Therefore to modify a request that has been emitted, i.e., to reconsider the current control, the monitoring system must take the "request/report" sequence into consideration. Thus, a monitoring system following the control hierarchic levels and the maintenance policies needs is desirable (Ly *et al.*, 2000).

A message flow is established between the lower and the higher levels, informing maintenance parameters (e.g. cost functions, time and rate) when it is applied to the lower level. Then, the system's unavailability may be evaluated at the higher level. Inside a CMM node a communication process (synchronization) is also observed between a reference model (e.g. equipment, workstation), the control model and the maintenance model. This allows the information system to be updated through the monitoring system and the execution of maintenance policies.

Maintenance, according to (Ly *et al.*, 2000), is defined as a group of technical and administrative actions, including supervision and control operations, to maintain (*preventive/predictive maintenance*) or re-establish (*corrective maintenance*) an entity to a specific state or to specific safety operating conditions (RAMS – reliability, maintainability, availability and safety) (Ly *et al.*, 1999). Maintenance policies can be classified in four great categories (Simeu & Sassine, 2001): corrective, preventive, predictive and mixed. In all four cases, triggering a maintenance operation is a decision process based on the state (measured or estimated) of considered resources. The opportunistic maintenance (Bérenguer *et al.*, 2004) may be also considered by modelling maintenance operations grouping procedures, which are used to take advantage of scale economies due to economic or technical dependences between components (e.g. a maintenance operation on a component triggers the maintenance of the complete line).

The triggering of maintenance tasks through a continuous decision process inspired us to enrich the CM module (Zamai *et al.*, 1997) with a maintenance module and then to define the *control-monitoring-maintenance (CMM) model*, as shown in Figure 1.

## Control-Monitoring module

First, let us consider the control-monitoring module. Each node is made up of the following elements:

- *Control Model*: comprises the operation sequence to be executed, which corresponds to a specific process handling.
- *Reference Model*: it is a process model that describes its possible states. The module's state is verified at the moment of a control request and at the moment a process signal (report) is acknowledged. The block's essential role is to continuously maintain the most perfect image of the real process's state.

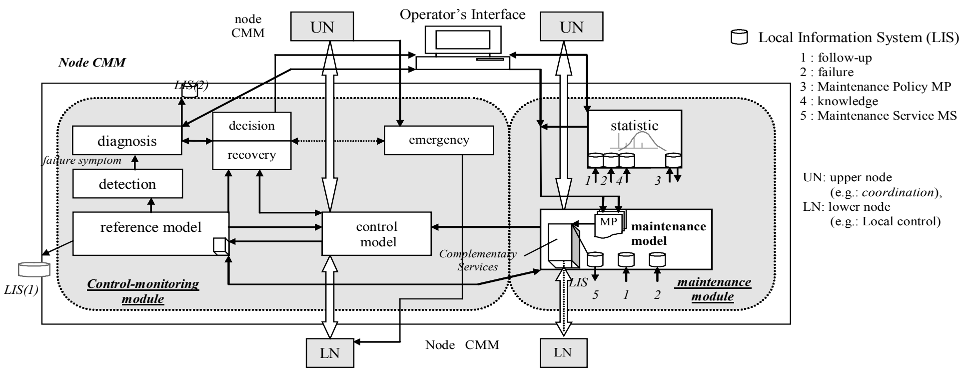


Figure 1. Control-Monitoring-Maintenance (CMM) Module

- *Detection*: the reference model is connected to the control model – it evolves in parallel and in real time during current operations of the process. At the moment in which the control model emits a request to the process, e.g.: starting an operation, a request is simultaneously transmitted to the reference model, which verifies the state's consistency, and estimates a temporal window for a process event to occur (end of operation). A *direct control monitoring* is characterised. If the control model within the allocated temporal window receives the report issued from the process, the control and the process model evolve simultaneously. Otherwise, the reference and control models can no longer evolve. At this moment it is possible to conclude that a process fault (equipment breakdown) just occurred, based on this non-consistent event, or based on a temporal signature that characterizes a failure evolution (in a *process indirect monitoring* approach). Moreover, the temporal causality observation of the events allows a progressive degradation evaluation of the manufacturing functions, which lead to a deviation of the production flow (in an *indirect predictive monitoring* approach). In fact, process reports are temporally analysed, regardless of the orders previously sent by the control part. In case of misbehaviour (a time drift on the events report), symptoms are generated and sent to the diagnostic function. The diagnosis module is thus required. Critical symptoms are also sent to error recovery in order to determine which actions have to be immediately performed to guarantee human and equipment safety.

- *Diagnosis*: it carries out the identification of the incident to which symptoms have been acknowledged. The diagnosis is generally broken down to three sub-tasks: *localization* (to find a functional sub-set of failing process components), *identification* (to refine localization by identifying the origin of a failure) and *prognosis* (to determine the consequences of a failure and to analyse its potential consequences and to prepare data required by the recovery function). The diagnosis is simple when it deals with a non-ambiguous symptom; even though it may also need a more sophisticated treatment using, for instance, an information system that completes the information that reports the absence of a process report (Chaillet *et al.*, 1997). The diagnosis engine is based on an algorithm that interprets the causal temporal signatures that characterize the different failures. The linear logic associated to a time fuzzy Petri net may be utilized as in (Künzle *et al.*, 1999).
- *Recovery decision*: its role is, according to diagnosis information (prognosis), to modify the control models, activate urgent procedures, trigger recovery procedures and, finally, decide about the propagation of failure treatment to the upper level.
- *Emergency*: provides the possibility, for the decision block, to immediately take action over the process, carrying out pre-defined and priority sequences (re-start, setting idle positions, etc).
- *Interface operator*: it is the user interface that allows the dialogue with a human operator every time his intervention is necessary. The operator has a central decision role.

The *monitoring process* follows a detection-diagnosis-recovery sequence. A confinement and propagation mechanism from the decision block decides if the fault is treated at the proper level (confinement) or if a request must be emitted to the upper level node (propagation).

**The maintenance module – the CMM node**

Figure 1 shows the architecture of a *control-monitoring-maintenance model* (CMM) at a given level. The insertion of the maintenance module did not modify the functionality of the described CM module's elements.

First, it is necessary to point out the purpose of the *decision* and *recovery* block concerning the CMM structure. As soon as this block is requested by the diagnosis block, it triggers different actions. If there is a risk to the operator or the process, the decision block triggers an emergency procedure and informs the upper level. Otherwise, it establishes a recovery point and the specific sequence makes it possible to access it. If the expected state is not coherent with the upper level's vision, the decision block informs about it; if no recovery process can be established, it sets the system to a maintenance state, informs the upper level and requests the operator. This is the *corrective maintenance* scenario. In this case it is necessary to "repair the defective material", i.e., eliminate fault effects in order to reach the system's regular operation status. This requires human intervention. The operator can access a maintenance module that offers a group of maintenance operations that are not necessarily the same as those of the control block. The control module remains in a blocked state during all intervention period. At the end of the maintenance activity, the system is redirected to a coherent state concerning the control model by the maintenance module, which authorizes its evolution.

The maintenance module consists of two blocks: the *statistic block* and the *maintenance model*. The purpose of the *statistics block* is to use all information issued from the process and control (process data registering) to calculate, estimate and establish a preventive and predictive maintenance plan. It assigns to some transitions of the maintenance model Petri net a transition rate with exponentially distributed triggering time. Random planning of maintenance policies or failure and repair rates are so modelled. The operator is informed that a preventive/predictive maintenance operation has become necessary. This block is supported by a *Local Information System* (LIS). The LIS is updated by different CMM module blocks and by external information (operators, equipment information, maintenance policies, etc). Concerning maintenance, it presents the following structure:

- *LIS* (*policy*): updates the maintenance intervention database. This registering makes future interventions easier;
- *LIS* (*knowledge*): contains information supplied by operators (experience return), information and indicators about the production system (MDT, MTTF, MTTR, MUT) supported by physical measures from dedicated sensors (vibration, temperatures, etc.). The prognosis function is performed to estimate the remaining life-time of the element leading to a direct predictive maintenance policy;
- *LIS* (*follow-up*): memorizes all control activities and plant events reports and their start and end dates; it enables to keep a control and a process image so as to support the diagnosis algorithm when a failure occurs or a deviation symptom comes about (indirect predictive maintenance policy);
- *LIS* (*failure*): memorizes information about detection, diagnosis and the decision regarding a failure.

In addition, it can be used to update the reference models' temporal windows in order to estimate the average operation time, so as to have a more precise representation of the process and to support the prognosis function.

The *maintenance model* suggests a group of services and/or sequences of specialized operations that are linked to a maintenance policy and that are not necessarily foreseen by the control under regular operation. A similar context may be found in (Ghoshal *et al.*, 1999), where some concepts were taken into account and adapted to our approach.

Maintenance is triggered by the operator after an unresolved fault case – it is the *corrective maintenance* policy or when triggered by the statistic block - it is the *preventive and predictive maintenance*. When maintenance is required (corrective, preventive or predictive), the modules' maintenance model inhibits all pre-set operation sequences (regular operating conditions) at the control model level. At this point the maintenance module takes up control of the process. The maintenance mode is, therefore, synchronized with the evolution of the reference model. In fact, it is important to take account of the process restrictions in order to provide a safety mechanism, making it impossible for the operator to trigger operations that are not in conformity with the process state. It is necessary to mention that, prior to any maintenance procedure, an image of the control state is captured by the local information system (LIS) to replace, after the intervention, the process and control into a coherent state.

The communication with the upper level consists in informing the maintenance state and, eventually, the estimated duration to implement the maintenance policy. This information is received by the upper maintenance module (node), which informs the control-monitoring module. The acknowledge of this information by the upper CMM module may lead to a reconfiguration process (Berruet, 1998), (Silveira *et al.*, 2000). The reconfiguration process consists of updating the FMS's architecture's flexibility to compensate the lack of services caused by the faulty resource. This can result in a simple displacement of the operations' sequence or the use of available resources, thus enabling the expected services.

## APPLICATION TO A ROBOT-DRIVEN FLEXIBLE CELL

### The flexible cell

The manufacturing cell is composed by four *working stations* served by a *conveyor system* and its *pallets* with parts to be treated. Each working station has a *robot* and a *vision system,* two parts stocks and a working desk. This cell is represented in Figure 2. This working station can perform assembly, disassembly, control and calibration operations.

The cell's *functional organization* is hierarchic and modular, structured in 5 levels: i) *Robots and local control*, vision systems and conveyor system zones at the lowest level; ii) The *coordination level* is organized into a working stations *local coordination* (robot, vision system), a *conveyor system coordination* (organized and controlled by 5 modules) and a general coordination; iii) At the highest levels, the *supervision, scheduling* and *planning* (production management).

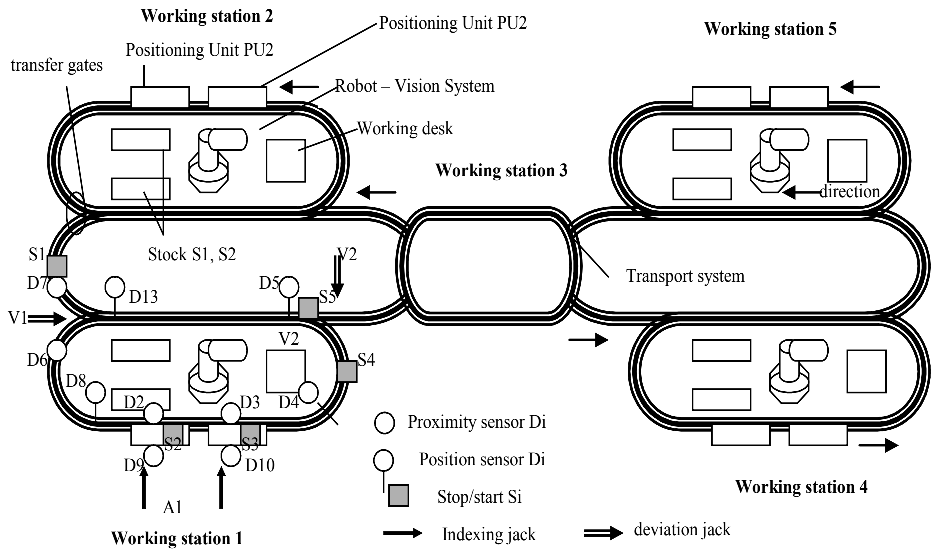


Figure 2. Robot-driven flexible cell

**The CMM module**

The *functional* structure of a local coordination CMM node is shown in Figure 3. It proposes a more flexible structure to allow the choice and the configuration of a service issued from the upper level (taking a set of pre-defined services into account). Thus, the node's functionality and flexibility increases by offering of this set of services in a layer and modular organization, leading to a local 'virtual hierarchy'. This results in a better interface with the upper (*general coordination*) and lower levels (*local control of robots and vision systems*). All this functionality is extended to the maintenance module.

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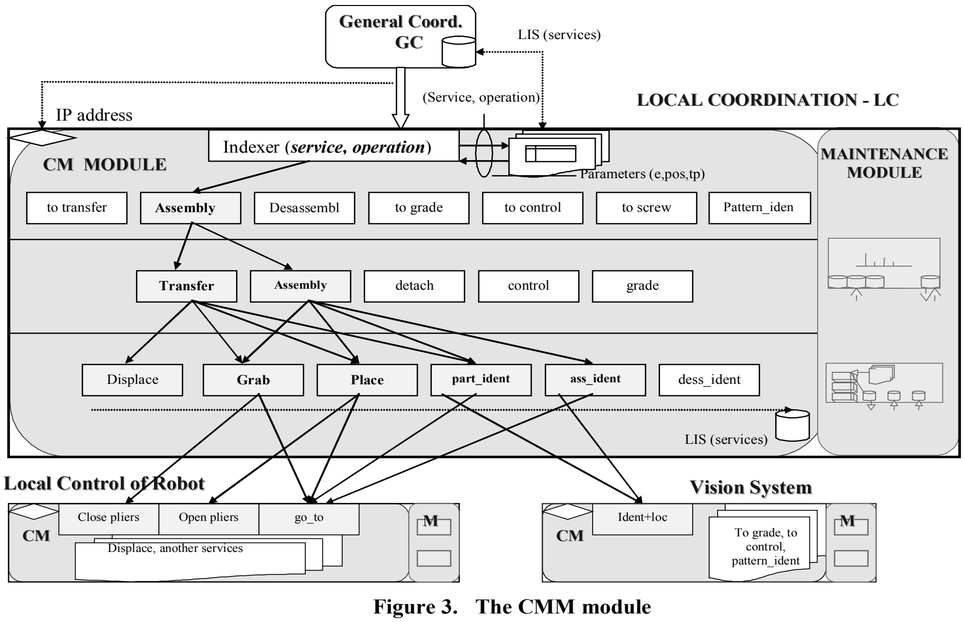


Figure 3. The CMM module

Let us start with the *assembly* of a spare part issued from the stock, on top of another part located above a working desk. The *control, reference and maintenance* models concerning this coordination level are described in Figure 4, and make up the CMM coordination module.

The representation of these models is based on *Petri Nets with Objects (PNO),* where the tokens hold the information (token attributes). The interpretation associated to transitions based upon these attributes leads to the execution of tests and actions (Zamai et al., 1997). In the maintenance PN model, stochastic rates are associated to some transitions that model the random planning of a maintenance policies (preventive maintenance - $\beta_{pm}$) as well as failure and repair/maintenance intervention rates (failure/corrective maintenance - $\lambda_{cm}$, duration and preparation rate - $\tau_c$, $\tau_p$, repair / maintenance intervention - $\mu$) . A Markov graph (array) is considered in the statistic block for a numerical simulation and evaluation.

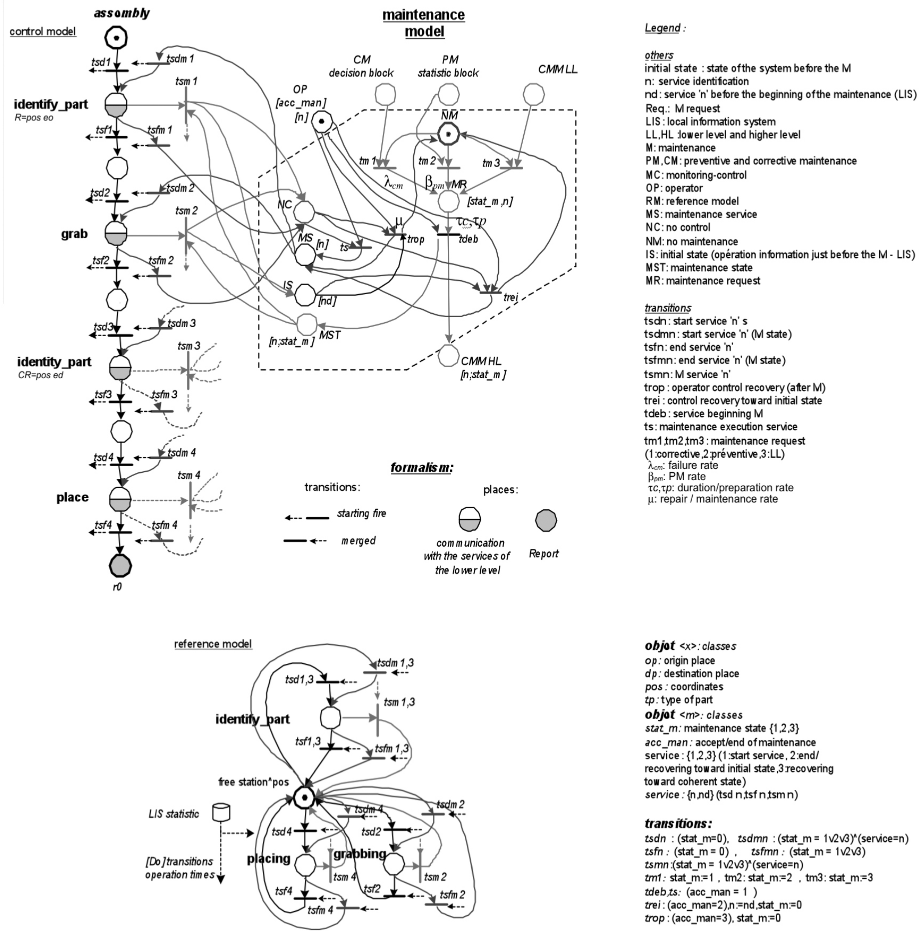


Figure 4. CMM reference-control-maintenance models for coordination of working station

Let us consider the control model. The *assembly* service starts a sequence of low level services: '*identify_ part*' service, which identifies the part's location in order to recover it (offered by the vision system's local control), '*grabbing*' service which grabs and moves the part from and into a placing position, '*placing*' service which corresponds to the assembly part and '*grabbing*' service for the removal of the assembly part (offered by the robot local control (Figure 5)). The associated reference model represents the process restrictions (mutual exclusion of operations and estimated operational times).

Communication between these models is implemented by means of a transition fusion method: as soon as the service control model 'part_*identification*' is requested, which corresponds to firing transition '*tsd1*', the '*tsd13*' transition, associated to transition '*tsd1*' at the reference model, is simultaneously fired (under the condition that its input place '*free_station*' is marked, meaning that the requested service is coherent with the process state). Therefore, the reference model evolves towards the '*part_identification*' state.

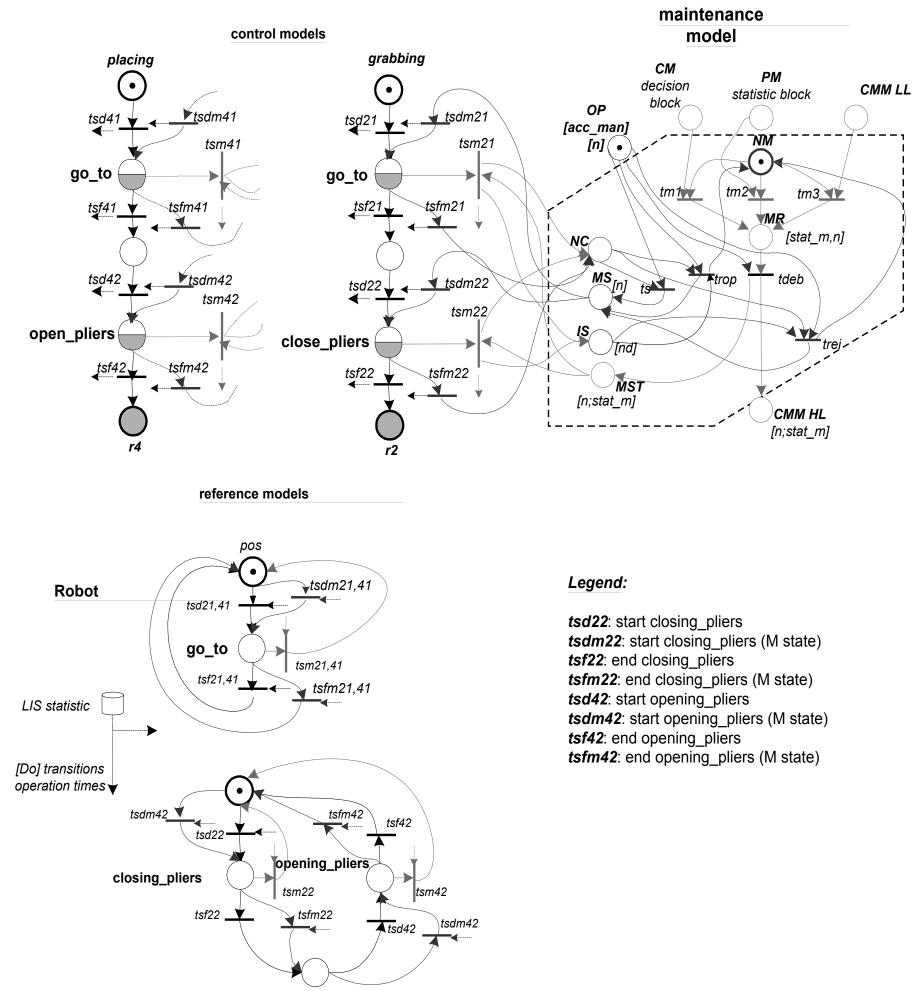


Figure 5. Local command CMM models for robots

The request is transmitted to the lower level, in this case, the vision system's local control. If the lower level execution report is not received within a temporal window defined by the reference model, the reference and control models can no longer evolve. A failure is detected and the monitoring process is triggered (detection, diagnosis, recovery).

If the execution report is received within the temporal window, the control and reference models can evolve (simultaneous firing of *'tsf1'* and *'tsf13'*). The reference model evolves towards the *'free_station'* state and the control model can request the *'grabbing'* service. Therefore, a simultaneous firing of *'tsd2'* occurs in the control and reference models and the latter also changes to the *'taken'* state. The service request is transmitted to the lower level, in this case, to the robot's local control.

At this level, the control model carries out a sequence of elementary controls over the process: *'go_to'*, then *'close_pliers'* (Figure 5). Two reference models represent the process' behaviour associated with the pliers and the arm movement. The evolution of the control and reference models is made as described previously. When this last sequence operation (*'close_pliers'*) ends, an execution report of the *'grabbing'* service (*'cr2'*) is transmitted to the CMM module's upper level. Then, the *'place'* and *'grab'* services are executed.

Let us suppose that a failure is detected at the end of the final *assembly* part operation: the *'close_pliers'* end-of-execution report is not received within temporal window. Thus, the decision block requires a corrective maintenance action from the operator (*CM-tm1-MR* sequence at the maintenance model of the CMM module's local control).

The operator acknowledges the module in a maintenance state and the upper level is informed about it (*OP-tdeb-MST/CMM NS* sequence). At the upper level, this information will be taken into account by the decision block and by the operator, who will decide, or not, about also placing the module in the maintenance state (*CMM LL-tm3-MR-tdeb-MST*). The module's maintenance state means the suspension of the on-going operation and its registering due to its recovery (*MST-tsm22-NC/IS* sequence).

At this moment the operator is able to require services or operations available in the control model, or trigger operation sequences that are different from the regular control (*OP/NC-ts-MS-tsdmn*). The detection mechanism still considers the process' restrictions through the reference model (transitions *'tsdmn'* and *'tsfmn'*). Sequences, tests or maintenance operations depend on the operator's experience and can be formulated by means of a rule-based system (expert system). It is possible to use the local information system's (LIS) data as a reference: failures historic data, interventions maintenance policies adopted, MTBF, MTT indexes, etc. Considering our case, when failure at the *'close_pliers'* service is detected, the operator is able to request:

- pliers opening (*OP/HS-ts-MS-tsdm42-open_pliers sequence*), and if the end-of-execution report (opening/closure signal value is acknowledged and the strength sensor is in state 0) is received within the temporal window (leading to firing *tsfm42* and marking *NC*), it is possible to conclude that the opening/closing pliers device is working.

- pliers repositioning (*OP/NC-ts-MS-tsdm21-go_to-tsfm21-NC* sequence) to make a pliers closing test with maximum safety;
- closing the empty pliers (*MS-tsdm22-close_pliers* sequence). If the end-of-execution report (value of the closing/opening signal is acknowledged and the strength sensor has an empty closing value) is not received within the time window, it is possible to conclude that the closing device is not working (interruption of the air supply, for example).

Once the failure is repaired, the operator is able to perform new tests, requesting a specific part in the stock (*'identify_part'* service of the CMM coordination module, after '*taking*' and finally '*placing*' it in the stock, for example). And finally, the operator must replace the control into a coherent state – to the breakdown initial state (registered by the *IS* location's stick), i.e., at the beginning of the *'taking'* service (*OP/NC/IS-trei-MS-tsdm2 sequence)* or proceed to the finalization of the suspended operation, before leaving it to the general control (*OP/NC/IS-trop-MS-tsdm2 sequence*). In both cases the reference models are equally replaced into coherent states. All interventions are registered in the Local Information Systems (LIS policy) to make future interventions easier.

## CONCLUSION

This study presented a hierarchic and modular control-monitoring-maintenance architecture, organized in CMM modules. In each module the interaction of a control module, process's reference models (allowing the detection of failures) and a maintenance module (consisting of a maintenance model and a statistics module) can be observed. This module allows different maintenance policies to be carried out - corrective and preventive/predictive ones.

The statistics block, coupled to a local information system, enables the registration of all the information issued by the process and control, it estimates and establishes a preventive/predictive maintenance plan and helps the operator during a maintenance intervention. The maintenance model PN may simulate the system's stochastic behaviour when subject to failures and maintenance procedures and repairs.

The operator can access, via maintenance model, the services and operations offered by the control and can sequence them differently from the expected process. In addition, it is possible to, eventually, access services that are available, but are not being used in the current process. The evolution of reference models during the control stages and during the maintenance stage results in an assurance of a coherent use of the process. This integration process, the maintenance tasks integrated into the control and monitoring structure, are the main advantages of our approach.

The proposed architecture is actually being implemented in a robot-driven flexible cell, connected to the Ethernet TCP/IP. Therefore, it is necessary to study the problems presented in a remote maintenance context, e.g.: the remote configuration of the CMM modules, network and devices, as well as the reliability, safety and real time conditions. Moreover, the planning and scheduling levels will be considered in detail leading to the definition of interfaces with the CMM nodes.

The CMM architecture (its models) is based on a development cycle methodology that characterizes the following steps: modelling, analysis/simulation and implementation of the CMM modules. Then, the maintenance aspects may be taken into account from the concept stage to the operation stage of a flexible manufacturing system. The proposed modelling approach based on Petri nets allows a modular optimisation of the maintenance procedure.

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# Manufacturing strategy incorporated in aggregate production planning through a multi-objective linear programming model

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**Abstract**
Aggregate Planning activity is a relevant stage of the production planning process and has been regularly discussed in the literature for almost 50 years. It seeks to suggest a production strategy in order to meet demand, given capacity constraints. This paper presents a model based on multi criteria decision analysis to overcome the problem of aggregate planning. This decision model takes into account performance objectives obtained in the manufacturing strategy planning process. To do so, the decision maker chooses the most appropriate combination of resources to meet foreseen demand, in accordance with trade-offs amongst the performance objectives. Therefore the resulting aggregate plan reflects the competitive factors of the business. That is, the proposed decision model allows the implementation of the manufacturing strategy by the production function.

**Keywords:** Aggregate Planning, Manufacturing Strategy, Multi Criteria Decision Analysis, Multiple Objective Linear Programming, Step Method.

## INTRODUCTION

Aggregate Planning is an important topic that has been regularly discussed in the literature for almost 50 years. Despite several works having been published in this area, most of the models developed that consider multiple objectives only consider different kinds of production costs. Recently, some papers have used new objectives in their models of aggregate planning, by considering new criteria such as variations in manpower, the tangible and intangible costs associated with the planning alternatives, and so forth.

Recently published models for aggregate planning problem use concepts of fuzzy sets (WANG & FANG, 2001; WANG & LIANG, 2005), stochastic programming (KIRA et al., 1997), multi-objective tabu search (BAYKASOGLU, 2001), genetic algorithms and multi-objective genetic algorithms (STOCKTON et al., 2004th; STOCKTON et al. 2004b; LI & MAN, 1998) and accounting consequences of the losses in aggregated planning (PIPER & VACHON, 2001).

In spite of some authors having used a multiple criteria approach for the aggregate planning problem, no-one has sought to integrate the objectives or goals defined in manufacturing strategy to the objectives and strategies (aspects of manpower, stock costs, regular production regime, outsourcing regime and other intangible costs) of aggregate planning. In this paper, a multi-objective model for aggregate planning that includes the context of manufacturing strategy in the aggregate planning of production will be presented.

In order for aggregate planning to be aligned with the manufacturing strategy adopted by the company, the winning aspects of orders (performance objectives) will be optimized to increase the company´s competitive advantage. So the production alternative chosen will help the production function to implement the manufacturing strategy.

In this paper, an expression (Equation 3) is proposed to quantify those winning aspects of orders. This expression will be maximized to achieve the best performance in these winning aspects, so that, in the end, it will be possible to choose a compromise solution, considering all the winning aspects, which implies best sales.

## AGGREGATE PLANNING

Aggregate Planning represents one of the most important decisions in the medium term, by forming a connection between Capacity Planning and Production Programming and Control (PPC) (SLACK et al., 2003; MONKS, 1982; HEIZER & RENDER, 1993; GAITHER & FRAZIER, 1999; DAVIS et al., 2004).

Aggregate Planning consists of drawing up a strategy to meet demand. To make it feasible, several changes in production level will be necessary to follow demand forecast in the horizon planning. This horizon planning takes place in intervals between six and twelve months in most of cases. This balancing can be undertaken by acting on the productive resources capable of influencing and changing production capacity in the short and very short term. It seeks to combine these productive resources in a way to meet the demand and simultaneously reach the minimum cost possible.

To keep production in balance with demand, several options are used such as hiring and firing employees, making use of overtime, subcontracting a part of production, accumulating stocks in the months of low demand and using them to cover excess demand in months of high demand, and so on.

However, Aggregate Planning can be used as an inverse guide, when the problem to be tackled is not a deficit in production, but rather a deficit in demand. In this sense, the search will be to eliminate loss-making resources, by seeking to reduce production costs so that these might be adapted to periods of insufficient demand.

Each one of these alternatives can be related directly and / or indirectly to a cost. In considering these costs, the models of Aggregate Planning seek a solution that minimizes the total production cost for the horizon of time over which the planning is made. To do so, an analysis is made of the costs involved in compiling a set of production alternatives to change the production levels in each period t, where these costs are represented by *PCt* (*Production Cost* in the period *t*). In this way, the total production cost for the n periods is:

$$PC = \sum_{t=1}^{n} PC_t \qquad (1)$$

The Production Cost in each period t includes costs that vary according to the number of employees hired/ fired (*At, Dt*), the number of units stored in the stock (*STt*) and the number of units produced in each of the respective production regimes (*Rt, Ot, St*). This cost can be expressed as in Equation 2:

$$CP_t = C_r r_t + C_o o_t + C_s s_t + C_D D_t + C_A A_t + C_{ST} ST_t \qquad (2)$$

An Aggregate Planning solution determines the combination of each combination of production alternatives in each period such that, at the same time that production meets demand, the total production cost (*PC*) is minimized to the smallest possible amount.

Among the models that assume that the variation of costs is linear, the literature presents the Model of Trial and Error and the Linear Programming Model as the most well-known. Eilon (1975) presents three other models. However, the two models previously mentioned appear in the literature as the best known.

## MANUFACTURING STRATEGY

Manufacturing strategy is defined in the literature as a collection of decision models to determine structure, resources and infra-structure of a production system. However, Miller & Hayslip (1989) define manufacturing strategy as a projected pattern to production alternatives made to improve results on the performance objectives and support the business strategy.

For Wheelwright (1984), the main objective of manufacturing strategy is to develop and support durable competitive advantages. Thus, an efficacious strategy may not imply production with maximum efficiency, but production which fits in with business needs. For this reason, it can be concluded that decisions made in this field might consider a multi-criteria approach, because it does not make sense to consider only one single objective optimal solution (for example, Cost), but a compromise solution where all objectives which represent the business needs have been considered (which may not lead to maximum efficiency), and all objectives have obtained the best results considering the proportional importance to business needs so that, in the end, durable competitive advantage can be achieved.

There are many concepts and classifications about the aspects that bring competitive advantage in manufacturing. Miller & Roth (1994) summarized and developed one taxonomy for manufacturing strategy. Miller & Roth (1994) used cluster analysis to identify eleven aspects to competitive advantage in manufacturing strategy. These aspects are Low Price, Design Flexibility, Volume Flexibility, Conformance, Product Performance, Delivery Speed, Dependability, After-Sales Service, Publicity, Broad Distribution and Broad Product Line.

### Performance Objectives

In the literature, lists of these competitive aspects (capabilities) can generally be summarized into five performance objectives to achieve competitive advantage based on manufacturing. These objectives are Cost, Quality, Dependability, Flexibility and Speed (HILL, 1993; SLACK et al., 2003; SLACK, 1992).

As to Quality, manufacturing strategy basically seeks to improve product quality through the reduction of the non-conformance item index. Making “better products” can mean several things, from “deluxe products” and “built-in quality” discussed lately for all dimensions proposed by Garvin (1987).

The objective Speed seeks to make minimize the lead time to produce and deliver an order. To achieve good results for Speed, it is necessary to improve acquisition processes and all logistics operations. In manufacturing strategy, the speed and dynamics of releasing a new product is also related to this performance objective. This approach is considered very often in technology industry.

Dependability means the capability of the production system to estimate and accomplish order / delivery deadlines, keeping the product's integrity until it is under the client's responsibility.

The objective Flexibility can have many meanings like Quality, because there is a wide field where flexible capabilities are needed in a production system, so Flexibility can take into account the number of models on offer, its capability for adapting to different production levels, being able to adapt orders to special client requests and being able to handle special clients, for example. In the end, what should be expected from a good performance in Flexibility is the capability to satisfy different needs in production.

For Cost, there is only one meaning: to minimize production costs and consequently to minimize product price for customers or to maximize profits for the company. Maybe that is the oldest objective, or in other words, the "natural objective" of any industry. That is why, in most cases, it is one of the most important objectives in production systems.

## Performance Objectives Classification

To support the decisions made in a manufacturing strategy context, it is necessary to establish the priority between the performance objectives. Hill (1993) proposed a performance objectives classification which gives one easy way to prioritize these objectives, taking into account the competitive value or utility, given an improvement in each objective.

These objectives are classified into Order Winners Criteria and Order Qualifiers Criteria. Figure 1 shows the behavior of managerial effort to improve the level of performance objective results in terms of competitive advantage or competitive value to manufacturing.

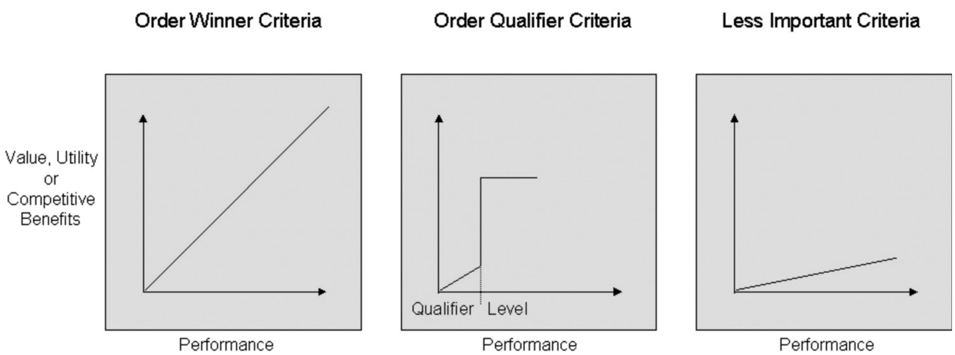


Figure 1 - Competitive Benefits from Performance Objectives, Adapted from Slack et al. (2003)

An object is an Order Qualifier Criterion if it has a critical level to be achieved. After satisfying this level, no improvement on this objective will be considered a competitive advantage. In other words, the customers will be satisfied when the manufacturing system achieves this critical level and any extra effort to give improvements in this objective will be a waste of managerial effort.

Some objectives do not have this property that makes customers satisfied. Each improvement in the objective will be perceived by customers and will represent competitive advantage. It can be used for resolving an evenly split outcome, making the decision favorable to the company which provides best levels for this kind of objective. So if a relevant objective follows this property, it is considered an Order Winner Criterion.

## STEM – STEP METHOD

STEM (Step Method) is a method of progressive reduction of the feasible region. It was developed by Benayoun et al. (1971). This method is part of the set of interactive methods of multiple objective linear programming that is an extension of the classical model of linear programming for the case in which more than one objective function is considered.

The procedures for this method consist of ensuring that for each interaction, the decision maker specifies an amount which he is willing to sacrifice in a given objective function, the one for which the decision maker is satisfied with the result obtained. Therefore, what is sought is to improve the result of those other functions, the values of which do not satisfy him.

The search for satisfactory solutions in STEM is made through minimizing Tchebycheff´s weighted distance to the "ideal" solution. This "ideal" solution is a fictitious alternative represented by a solution that assumes in each objective function the optimum value of these functions when optimized. It is hard to imagine such an alternative might exist, since this combination of values becomes infeasible due to the conflicts that almost always exist when multiple objectives are considered. This is a characteristic found in multi-criteria problems.

At each iteration of the method, an optimization problem is solved, into which are incorporated the decision maker´s preferences. Each one of these calculation stages reflects the choices that the decision maker made previously, and in which the decision maker´s preferences can be noticed since the feasible region has been reduced.

At the end of iteration, the decision maker finds a compromise solution obtained through the minimization of Tchebycheff´s weighted distance to the "ideal" solution. The decision to maintain this compromise solution or to discard it is made by the decision maker, and this decision determines if another iteration should begin or if the process should finish.

## PROPOSED MODEL

The proposed model seeks to ensure that a typical problem from the context of production planning allows the production function to implement the manufacturing strategy adopted.

A cost will associated with each alternative for meeting demand. Therefore, the proposed model seeks to find a strategy for meeting demand (obtained through Aggregate Planning) that is aligned with the defined manufacturing strategies, with regard to the priority and the established relationships among the performance objectives.

Thus, the manager (decision maker) can undertake the planning of the resources to be used in order to meet demand by prioritizing the performance objectives that best reflect the competitive factors of the business, and which represent consumers´ needs.

After defining the business strategy, the production managers define a manufacturing strategy so that the production function can develop the objectives and policies appropriate to their resources, by supplying the conditions necessary for allowing the company to reach its strategic objectives. Therefore, the performance objectives (HILL, 1993; SLACK, 1992) will be defined which will act as constraints (Order Qualifier Criteria, the production function should always satisfy a given minimum level of performance) and the others that should be maximized or minimized through an objective function (Order Winner Criteria).

The performance objective Cost appears traditionally in Aggregate Planning models through minimizing the total cost of production.

The other performance objectives (Quality, Dependability, Speed and Flexibility) should be maximized. In this paper, a standard form is defined which may represent them without loss of generality. However, the parameters of this function will have a different meaning for each performance objective. This standard form represents the average level of a performance objective. Equation 3 represents this function:

$$\max \quad Obj_k = \frac{1}{n}\sum_{t=1}^{n}\left(\frac{\alpha_{rk}r_t + \alpha_{ok}o_t + \alpha_{sk}s_t}{r_t + o_t + s_t}\right) \tag{3}$$

This equation presents a generic expression to represent the average level of a given performance objective, where $\alpha_r$, $\alpha_o$, $\alpha_s$ are parameters that have a specific meaning for each performance objective (Quality, Dependability, Speed and Flexibility), representing in a generic way a performance index for each production regime in the context of a given performance objective. The result of this objective function is the average value obtained for a given performance objective over the whole planning horizon (*n* periods).

However, the expression of Equation 3 is not a linear expression, which violates the linearity hypothesis considered for the model, which leads us to a simplification that guarantees linearity. Instead of using the expression suggested above, a similar expression should be used that maximizes the expression suggested previously.

$$\max \quad Obj_k = \sum_{t=1}^{n} (\alpha_{rk} r_t + \alpha_{ok} o_t + \alpha_{sk} s_t) \tag{4}$$

This expression gives a measure of the global performance regarding the accumulated performance in the whole planning period. Through Equation 4, it is possible to use linear programming, so allowing the choice of one among the several methods of multiple objective linear programming, optimizing the global measures of the performance objectives considered, and keeping the specific meaning (for each performance objective) defined for the parameters.

The parameters $\alpha_r$, $\alpha_o$, $\alpha_s$ are established through the company´s knowledge regarding relative performance among different production regimes in the performance objective analyzed.

The equations below represent the proposed aggregate planning model, where the first constraint represents the smallest level admitted for the Order Qualifier Criteria.

$$\begin{aligned}
&\min \quad C = \sum_{t=1}^{n} (C_r r_t + C_o o_t + C_s s_t + C_D D_t + C_A A_t + C_{ST} ST_t) \\
&\max \quad Obj_k = \sum_{t=1}^{n} (\alpha_{rk} r_t + \alpha_{ok} o_t + \alpha_{sk} s_t) \\
&s/a \\
&\qquad Obj_k \geq NObj_k \\
&\qquad ST_t \leq N \\
&\qquad r_t \leq u_r (E_{t-1} + A_t - D_t) \\
&\qquad o_t \leq u_h (E_{t-1} + A_t - D_t) \\
&\qquad s_t \leq C_s \\
&\qquad r_t + o_t + s_t + ST_{t-1} \geq d_t \\
&\qquad ST_t = ST_{t-1} + r_t + o_t + s_t - d_t \\
&\qquad E_t = E_{t-1} + A_t - D_t
\end{aligned} \tag{5}$$

The other constraints represent the relationships between the production alternatives and the productive system:

- capacity constraints on stocking products (*STt* < *N*);
- capacity in regular production regime by period ($r_t \leq u_r E_t$, where $E_t = E_{t-1} + A_t - D_t$);
- capacity of production under a regime of overtime by period ($o_t \leq u_o E_t$, where $E_t = E_{t-1} + A_t - D_t$);
- capacity in subcontracting production regime by period ($s_t \leq C_s$);
- demand to be satisfied in each one of the n periods ($d_t \leq r_t + o_t + s_t + ST_{t-1}$);
- volume of stocked products in period t ($ST_t = ST_{t-1} + r_t + o_t + s_t - d_t$)
- number of employees in period t ($E_t = E_{t-1} + A_t - D_t$)

## NUMERICAL APPLICATION

In this section, a numerical application will be made to illustrate how the Multi-objective Aggregate Planning Model proposed can be used. For this, the numerical application was drawn up using data and characteristics found in the literature. The model presented will be applied on this application.

A fictitious company was considered where Cost and Dependability are considered Order Winner Criteria, so they should be optimized.

The other performance objectives (Quality, Flexibility and Speed) behave as Order Qualifier Criteria. These three classes of restrictions will not be incorporated into this application, because the hypothesis will be assumed that all production regimes and whatsoever combination of these do not have a performance level less than the minimum levels demanded by the customers. Therefore, there is no need to consider the Order Qualifier Criteria restrictions in this application.

The quantification of the Dependability parameters is given by the probability that an order is fulfilled on time. To find this value, company knowledge could be used about the relative frequency of delays in deliveries by each production regime. These probabilities are the parameters of the second objective function of the multiple objective linear programming model given below:

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$$\min \quad F_1 : C = \sum_{i=1}^{n} (250r_i + 350o_i + 425s_i + 12500A_i + 36500D_i + 30ST_i)$$

$$\max \quad F_2 : Dep = \sum_{i=1}^{n} 0{,}95r_i + 0{,}80o_i + 0{,}70s_i$$

$$s/a$$

$$\begin{aligned} & ST_t \leq 1500 \\ & r_t \leq 90(E_{t-1} + A_t - D_t) \\ & o_t \leq 30(E_{t-1} + A_t - D_t) \\ & s_t \leq 600 \\ & r_t + o_t + s_t + ST_{t-1} \geq d_t \\ & ST_t = ST_{t-1} + r_t + o_t + s_t - d_t \\ & E_t - (E_{t-1} + A_t - D_t) \leq 10 \\ & ST_0 = 0 \\ & E_0 = 8 \end{aligned} \qquad \textbf{(6)}$$

where *t=1,2,...,12*.

The data on the problem can be visualized in the equations that comprise the model above, except for the demand foreseen which is described in table 1 below:

Table 1 – Foreseen Demand

| Month (t) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Demand (d) | 1200 | 1500 | 1250 | 1800 | 1350 | 2200 | 2100 | 2300 | 1580 | 1470 | 1350 | 1100 |

Several methods of multiple objective linear programming can be used to find a compromise solution to this problem. However, choosing STEM is justified because it is an interactive method that can be implemented easily (which adds greatly to the viability of using it) in order to minimize Tchebyneff´s weighted distance to the "ideal" solution independently of the decision maker, thus leaving subjectivity only to the stage of exploring the frontier of efficient or non-dominated solutions. During this stage, the decision maker looks for a solution to the problem by making trade-offs among the values obtained for each objective. By being about a numerical application of a fictitious example, only a few points will be considered in order to demonstrate how an efficient compromise solution can be chosen for this problem through this method of multiple objective linear programming.

In order to examine the problem thoroughly, the first stage of STEM consists of optimizing each one of the objective functions. The optimum value of each objective

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function represents a "goal" which one desires to reach. This "goal" should be an "ideal" alternative, which has the greatest performance in all its objective functions.

The optimum found for the Cost objective function was a total annual cost of R$ 6,158,500.00. If this solution were chosen, the Dependability level would be 85.8%, i.e. an expected value of 16,490 units delivered within schedule.

When Dependability was optimized, the maximum result was 91.4% i.e. an expected value of 17.550 units delivered within schedule. To reach this performance level of Dependability, a total annual cost of R$ 6,913,600.00 is necessary. This increase of the index of Dependability is achieved due to the increase of stock levels, which provide a safety margin for the company.

In this stage, the decision problem consists of finding an intermediate alternative that is more balanced between the two criteria defined for this problem. The following stage of applying the STEM method consists of finding a feasible solution that minimizes Tchebycheff´s weighted distance to the "ideal" alternative. The weightings used were obtained through the STEM procedure for calculating weightings. However, the alternative that minimizes Tchebycheff´s weighted distance is the alternative that minimizes the total annual cost, not taking the Dependability objective into account. This is due to the fact that the variations occurring in the total annual cost are much greater than those occurring in Dependability.

Moving on to the following stage of STEM where there is interaction with the decision maker, the objective function of total annual cost was relaxed to improve the values of the objective function of Dependability that were not considered satisfactory

A decision maker could evaluate the trade-off between the losses arising from the increase of costs and the strategic earnings obtained by increasing the number of products delivered within schedule. In looking for an intermediate solution and evaluating the cost possibilities, it was arbitrated that a maximum cost of R$ 6,550,000.00 would be considered satisfactory since this promoted a performance increase in Dependability that justified this cost increase.

The solution obtained by relaxing the total annual cost function was that, at a total cost of R$ 6,550,000.00, it is possible to obtain a Dependability level of 89.1%, making it viable to expect a value of 17,106 items delivered on schedule. The solution obtained for the recommendation is described in table 2 below:

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Table 2 – Final solution after the relaxation of the Total Cost

| | Alternatives to Assist Demand | Regular Production Regime | Overtime Production Regime | Outsourcing Regime | New Employees' Admission | Employees' Dismissal | Units in Stock | Number of Employees | Demand |
|---|---|---|---|---|---|---|---|---|---|
| Month | 0 | - | - | - | - | - | 0 | 8 | - |
| | 1 | 900 | 300 | 0 | 2 | 0 | 0 | 10 | 1200 |
| | 2 | 900 | 300 | 500 | 0 | 0 | 200 | 10 | 1500 |
| | 3 | 900 | 300 | 600 | 0 | 0 | 750 | 10 | 1250 |
| | 4 | 900 | 300 | 600 | 0 | 0 | 750 | 10 | 1800 |
| | 5 | 900 | 300 | 600 | 0 | 0 | 1200 | 10 | 1350 |
| | 6 | 900 | 300 | 600 | 0 | 0 | 800 | 10 | 2200 |
| | 7 | 900 | 300 | 600 | 0 | 0 | 500 | 10 | 2100 |
| | 8 | 900 | 300 | 600 | 0 | 0 | 0 | 10 | 2300 |
| | 9 | 900 | 300 | 380 | 0 | 0 | 0 | 10 | 1580 |
| | 10 | 900 | 300 | 270 | 0 | 0 | 0 | 10 | 1470 |
| | 11 | 900 | 300 | 316 | 0 | 0 | 166 | 10 | 1350 |
| | 12 | 900 | 300 | 600 | 0 | 0 | 866 | 10 | 1100 |
| | 13 | - | - | - | - | 0 | 866 | 10 | - |

This solution was considered satisfactory for illustrating the approach proposed in this paper in order to obtain a solution for Aggregate Planning Problem that is aligned with the manufacturing strategy adopted.

## CONCLUDING REMARKS

This paper has presented a multicriteria decision model to tackle the problem of Aggregate Production Planning that seeks to extend the priorities of manufacturing strategy for decision making in the context of Aggregate Production Planning. The proposed model quantifies the performance of the production alternative chosen in the aspects considered priority ones for a manufacturing strategy.

The application of this model allows the decisions taken in Aggregate Planning context (the amount of items to be produced in each production alternative for each period of the planning horizon, the stock levels along the planning horizon and the variations in manpower so that the demand foreseen is met) to be aligned with the manufacturing strategy adopted by the company, generating results that allow the production function to offer competitive advantage to the organization.

In the numerical application, use was made of an interactive method of multiple objective linear programming that could be implemented easily, thus making it viable to solve the problem contained in Microsoft Excel. Furthermore, this problem can be solved using LINDO, GAMS or any other optimization tool.

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# Application of nonlinear models to studies in the ergonomics area

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**Abstract**

This paper presents nonlinear models applied to studies in the ergonomics area. In general, these models evaluate the nature of the relationship between a group of Independent Variables (IVs) and one Dependent Variable (DV). In this study the interest is on the effect of the variables thermal perception ($P_t$); noise perception ($P_n$); age ($A$); time of service ($T_s$) on the working ability. The sample was constituted of 60 public bus drivers. The Chi-Square test was used to verify the significance between the final models and the intercept, thus analyzing the relationship between the dependent and independent variables. The Wald's test was applied in order to evaluate the consistency of the parameter estimates of the IVs. A logistic regression model was built including the variables $P_t$ , $P_n$ and $A$ as the IVs. Since $A$ has a greater influence on the working ability of the driver, another logistic regression model was constructed considering just this variable as the IV. It was concluded that when the bus driver's age increases by one unit, there is a 23.5% chance of his work ability to fall in the range of poor to moderate.

**Keywords**: Nonlinear estimation, logistics regression, work ability, perception, age.

## 1. INTRODUCTION

In the most general terms, the nonlinear estimation will compute the nature of the relationship between a set of Independent Variables (IVs) and one Dependent Variable (DV); it may be said that it is a generalization of the multiple regression methods called ANOVA and MANOVA; it essentially specifies some kind of continuity or discontinuity in the regression model. Thus, the DV can be specified to be a logarithmic function of the IV(s) an exponential function.

When allowing for any type of relationship between the IVs and the DV, two issues arise. First, what types of relationships make sense, i.e., are interpretable in a meaningful manner? A simple linear relationship is very convenient since it allows one to make straightforward interpretations. Nonlinear relationships cannot usually be interpreted and verbalized in such a simple manner. The second issue is how to exactly compute the relationship, that is, how to arrive at results that allow one to say whether or not there is a nonlinear relationship as predicted.

Some studies may generate data whose outcome for each individual is a binary, i.e., it may be represented only by two values, generally 0 or 1. There are, at least, four functions used in the data modeling whose variable is binary: logit, probit, complimentary log-log function and log-log function. In the field of the experimental human sciences and ergonomics, the logistics function has been very much used, not only because its theoretical functions are simpler, but, mainly, because of its simple interpretation as a logarithm of the chance rate (odds ratio). In the use of the logistics regression model, one might be interested in the effect of a specific risk factor or in the identification of various associated factors with the DV.

Traditionally, the studies involving a worker population search for reasonable associations between pathologies and probable risks factors (Cordeiro, 1991). In this way, it is notable the production of essays which study associations between the general decrease in the workers performance and the occupational exposure to environments with high thermal and noise levels. One of the main causes for this interest is determined by the effects of this exposure like the decrease in the alert state, and also the risk of enchaining some other health disturbances for these people (Cordeiro *et al.,* 2005, Fleig, 2004; Rodrigues and Magalhães, 2004; Pimentel-Souza, 2000).

Recent researches demonstrate activities related to transportation as one of high risk for physical and mental health of the worker, due to the occupational exposure factors, e.g. noise and thermal (Karazman *et al.*, 2000, Kloimueller *et al.*, 2000, Mello, 2000, Costa, 2003, Fleig, 2004).

In this work, we apply nonlinear estimation, namely the Logistic Regression to evaluate the effect of the environmental conditions, age and time of service on the working capacity of urban public bus drivers.

This paper is organized as follows. Section 2 presents a brief literature review of some works that had used logistic regression in the ergonomics area. Section 3 deals with the nonlinear estimation, emphasizing the main aspects of the Logistic Regression. Section 4 illustrates the Methodology used in this research. Section 5 contains the results obtained followed by some discussions. Section 6 presents some final considerations and concluding remarks

## 2. LITERATURE REVIEW

Several studies have applied nonlinear statistical techniques such as logistic regression to analyze ergonomics data.

Werner *et al.* (2005) in their work titled "Predictors of Upper Extremity Discomfort: A Longitudinal Study of Industrial and Clerical Workers" studied a cohort of 501 active workers. Cases were defined as workers who were asymptomatic or had a low discomfort score of 1 or 2 at baseline testing and went on to report a discomfort score of 4 or above on a 10-point visual analog scale. This change was considered clinically significant. Controls had a low baseline discomfort score and continued to have a low discomfort rating throughout the study. The risk factors found to have the highest predictive value for identifying a person who is likely to develop a significant upper extremity discomfort rating included age over 40, a Body Mass Index (BMI) over 28, a complaint of baseline discomfort, the severity of the baseline discomfort rating and a job that had a high hand activity level (based upon hand repetition and force). The risk profile identified both ergonomic and personal health factors as risks and both factors may be amenable to prevention strategies.

Murphy *et al.* (2007) did a cross-sectional study about back and neck pain among English schoolchildren and associated physical and psychological risk factors. They set out to identify the associations between ergonomics and other factors with back and neck pain. Self-reported questionnaires were used to record health outcomes and potential risk factors in state schools. Six hundred and seventy-nine schoolchildren from Surrey in the United Kingdom aged 11–14 years took part. Twenty-seven percent of children reported having neck pain, 18% reported having upper back pain, and 22% reported having low back pain. A forward stepwise logistic regression was performed with pain categories the dependent variables. Neck pain was significantly associated with school furniture features, emotional and conduct problems, family history of low back pain and previous treatment for musculoskeletal disorders. Upper back pain was associated with school bag weight (3.4 – 4.45 kg), school furniture features, emotional problems and previous treatment for musculoskeletal disorders. Low back pain was associated with school furniture features, emotional problems, family history and previous injury or accident. It is important to recognize the influence of physical, psychological and family factors in children's pain.

Zetterberg *et al.* (1997) studied 564 car assembly workers, 440 men and 124 women. Questionnaires, including work satisfaction, orthopaedic examination and exposure evaluation were performed. Women had more neck-myalgia and more physical signs from the hands, especially nerve related problems and tendinitis as compared to men. Impingement of the shoulder was equally prevalent among women and men, doing the same work. Women showed a higher work satisfaction than men. Stress at work correlated both to subjective complaints from all locations in the upper half of the body and to findings at the physical examination. A logistic regression analysis showed that subjective complaints from the neck, shoulders and feet correlated to less good work satisfaction, while work dissatisfaction was not correlated to any of the physical signs. Those having station-bound work showed less good relations to foremen/workmates and better to the work in comparison with the workstations at the assembly line.

Fogleman and Lewis (2002) studied factors associated with self-reported musculoskeletal discomfort in Video Display Terminal (VDT) users. The data were collected via a survey administered to 373 persons who use a VDT at a corporate office site; 292 of the surveys were returned (78%). Respondents were asked to report on symptoms for six body regions, as well as job requirement information, demographic information, and a question regarding non-occupational hobbies. The body regions included were: head and eyes, neck and upper back, lower back, shoulders, elbows and forearms, and hands and wrists. Descriptive information on these data was obtained through exploratory factor analysis, while logistic regression was used to estimate risk. The results indicated a statistically significant increased risk of discomfort on each of the body regions as the number of hours of keyboard use increases. Improper monitor and keyboard position were also significantly associated with head/eye and shoulder/back discomfort, respectively. These results emphasized the importance of workstation ergonomics and the need to limit the number of uninterrupted hours at the keyboard to reduce musculoskeletal symptoms.

Shipp *et al.* (2007) dealt with a study titled "Severe Back Pain Among Farmworker High School Students From Starr County, Texas: Baseline Results". This cohort study was among the first to estimate the prevalence of and examine potential risk factors for severe back pain (resulting in medical care, 4+ hours of time lost, or pain lasting 1+ weeks) among adolescent farm workers. These youth often performed tasks requiring bent/stooped postures and heavy lifting. Of 2536 students who participated (response rate across the three public high schools, 61.2% to 83.9%), 410 students were farm workers. Students completed a self-administered Web-based survey including farm work/nonfarm work and back-pain items relating to a 9-month period. The prevalence of severe back pain was 15.7% among farm workers and 12.4% among nonworkers. The prevalence increased to 19.1% among farm workers who also did nonfarm work. A multiple logistic regression for farm workers showed that significantly increased adjusted odds ratios for severe back pain were female sex (4.59); prior accident/back injury (9.04); feeling tense, stressed, or anxious sometimes/often (4.11); lifting/carrying heavy objects not at work (2.98); current tobacco use (2.79); 6+ years involved in migrant farm work (5.02); working with/around knives (3.87); and working on corn crops (3.40). Areas for further research included ergonomic exposure assessments and examining the effects of doing farm work and non-farm work simultaneously.

Feuerstein (2003) did a study of clinical and workplace factors associated with a return to modified duty in work-related upper extremity disorders. Return to work following treatment for a Work-Related Upper Extremity Disorder (WRUED) is affected by a variety of medical, workplace, and personal factors and returning to modified duty may ease the transition to normal work activities. This study surveyed 165 federal government employees (127 females, 38 males) who were unable to resume their normal work after filing a workers' compensation claim for a WRUED (<90 days from claim filing) and who volunteered for a randomized study of alternative case management strategies. Before randomization, participants completed a baseline survey of upper extremity (UE) symptoms, functional limitations, and workplace factors. At baseline, 58 participants (35%) were working modified duty and 107 participants (65%) were not working. Compared with participants working modified duty, those who were not working were more likely to report: (a) a diagnosis of mononeuropathy, Odds Ratio (OR) = 3.16 (95% Confidence Interval (CI) = 1.37 – 7.14) versus enthesopathy, (b) higher pain ratings, OR = 1.43 (95% CI = 1.01 – 2.01), (c) greater functional limitations, OR = 1.63 (95% CI = 1.11–2.38), and (d) higher level of ergonomic stressors, OR = 1.62 (95% CI = 1.09 – 2.43) in a multivariable logistic regression. Measures of high risk work styles (fast pace and working despite pain) were associated with greater perceptions of ergonomic exposure, but not with work status. The model had 87.9% sensitivity and 43.1% specificity to correctly classify those not working (overall classification 72.1% correct). The results suggested that modified duty for workers with persistent WRUEDs may be enhanced by assessing perceived functional limitation and ergonomic exposure as well as the type and severity of symptoms.

Sampaio *et al.* (2006) realized a study very similar titled "Work Ability and Stress in a Bus Transportation Company". Demographic, occupational and psychosocial characteristics affected the health and occupational performance of workers. The objective of the study was to elaborate a profile of the work ability and factors affecting it in a bus transportation company in Belo Horizonte, Brazil. The instruments used included a socio-demographic and occupational questionnaire, the Work Ability Index and the Job Stress Scale. Demographic information revealed that 85.7% of the 126 employees of the company were active workers, 98% were males with an average of 39 years of age (SD = 10) and 79 months at the company (SD = 68) and more than half reported had a low level of schooling. In terms of personal habits, 88% were exposed to one or more risk factors, especially a sedentary lifestyle. The average strain value (as a consequence of stress) was 0.78 (SD = 0.2) and 75.3% reported episodes of violence at the workplace. The work ability was good to excellent among 89% of the workers. Results from the logistic regression analysis showed that strain was the only significant variable related to Work Ability Index, (estimated odds ratio of 0.02). The results suggested that psychosocial factors presented the greatest association with work ability, and preventative and/or corrective measures should be implemented.

## 3. NONLINEAR ESTIMATION

The nonlinear estimation is a general fitting procedure that will estimate any kind of relationship between a DV, and a list of IVs. In general, all regression models may be stated as:

$$y = F(x_1, x_2, ..., x_j) \qquad (1)$$

In most general terms, the user is interested in whether and how a DV is related to a list of IVs. An example would be the linear multiple regression model. Hence:

$$y = \beta_0 + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + ... + \beta_p \cdot x_p + \varepsilon \qquad (2)$$

where $x_1, x_2, ..., x_p$ are constants, $\beta_0, \beta_1, \beta_2, ..., \beta_p$ are parameters denominated as partial regression coefficients and ε the residues. However, the multiple regression does not “know” that the response variable is binary in *nature*. Therefore, it will inevitably fit a model that leads to predicted values that are greater than 1 or less than 0. However, since these values are not valid the restriction in the range of the binary variable (between 0 and 1) is ignored if one uses standard multiple regression.

### 3.1 Logistic Regression Model (LRM)

According to Hosmer and Lemeshow (1989) and Casella and Berger (2002), the name logit stems from the fact that one can easily linearize this model via logit transformation. Suppose the quantity $\pi(x) = E(Y|x) = \beta_0 + \beta_1 x$ (this means it may be expressed as an eq. linear in $x$) represent the conditional mean of $Y$ given $x$ when the logistic distribution is used. The specific form of the logistic regression model used in this paper is shown in eq. (3).

$$\pi(x) = \frac{e^{\beta_0+\beta_1 x}}{1+e^{\beta_0+\beta_1 x}} \qquad (3)$$

The logit transformation used in logistic regression is defined, in terms of $\varpi(x)$, as follows:

$$g(x) = \ln\left[\frac{\pi(x)}{1-\pi(x)}\right] = \beta_0 + \beta_1 x \qquad (4)$$

The importance of this transformation is that $g(x)$ has many of the desirable properties of linear regression model. The logit, $g(x)$ is linear in its parameters, may be continuous, and may range from $-\infty$ to $+\infty$, depending on the range of $x$.

In addition, as in the case of linear regression, the strength of a modeling technique lies in its ability to model many variables, some of which may be on different measurement scales.

Consider a collection of $p$ independent variables which will be denoted by the vector $x' = (x_{1,} x_2, \ldots, x_p)$. For the moment it will be assumed that each of these variables is least-interval scaled. Let the conditional probability presented by the outcome be denoted by $P(Y=1|x) = \pi(x)$. Then the logit of the multiple logistic regression model is given by the eq. (5).

$$g(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_p x_p = \beta_0 + \sum_{i=1}^{p} \beta_i x_i \qquad (5)$$

where $\pi(x) = \frac{e^{g(x)}}{1+e^{g(x)}}$ (6)

If some of the IVs are discrete and nominal-scaled, e.g., race, sex, perception about environmental conditions, treatment group, and so forth, then it is inappropriate to include them in the model as if they were interval scaled. This is because the numbers used to represent the various levels are merely identifiers, and have no numeric significance. In this situation, the method of choice is to use a collection of design variables (or dummy variables).

After estimating the coefficients, a first look at the fitted model commonly concerns an assessment of the significance of the variables in the model. This usually involves formulation and testing of a statistical hypothesis to determine whether the IVs in the model are "significantly" related to the outcome variable. The method for performing this test is quite general and differs from one type of model to the next only in the specific details.

Two statistical tests have been suggested: Wald's and Score. The Wald's test compares the maximum likelihood estimate of the slope parameter, $\hat{\beta}_1$, to an estimate of its Standard Error (SE). The resulting ratio, under the hypothesis that $\beta_1 = 0$, follows a standard normal distribution. Before concluding that any or all of the coefficients are nonzero, it is necessary to apply the univariate Wald's test statistics:

$$W_j = \frac{\hat{\beta}_j}{SE(\hat{\beta}_j)} \quad (7)$$

The use of the Score test is limited by the fact that it cannot be obtained easily from some software packages. It's based on the distribution theory of the derivatives of the log likelihood. However, this test does not require costly computational task. Proponents of the Score test cite this reduced computational effort as its major advantage.

Two other methods may also be be used for estimating the coefficients: (i) noniterative weighted least squares, and (ii) discriminant function analysis. Grizzle *et al.* (1969) *apud* Hosmer and Lemeshow (1989) demonstrate that the logistic regression model is an example of a very general class of models that can be handled by their methods, that is, by using only one iteration in the process.

**3.2 Interpretation of the LRM coefficients**

The estimated coefficients for the independent variables represent the slope of a function of the DV in the IV. Thus, interpretation involves two issues: determining the functional relationship between the dependent and independent variables, and appropriately defining the unit of change for the IV.

In the LRM the link function is the logit transformation presented in eq. (4). For this model we recall that the slope coefficient, $\beta_1$, is equal to the difference between the value of the DV at $x + 1$ and the value of the DV at $x$, for any value of $x$, that is:

$$\beta_1 = g(x+1) - g(x) \quad (8)$$

In other words, the slope coefficient represents the change in the logit for a change of one unit in the IV $x$.

Consider a situation where the DV is dichotomous, i.e., $x$ is coded as either 0 or 1. Under this model there are two values of $\pi(x)$ and two equivalent values of $1 - \pi(x)$. These values may be conveniently displayed as shown in Table 1.

Table 1:Values of the logistic regression model when the DV is dichotomous

| Outcome (Y) \ Independent (X) | X = 1 | X = 0 |
|---|---|---|
| Y = 1 | $\pi(1) = \frac{e^{\beta_0+\beta_1}}{1+e^{\beta_0+\beta_1}}$ | $\pi(0) = \frac{e^{\beta_0}}{1+e^{\beta_0}}$ |
| Y = 0 | $1-\pi(1) = \frac{1}{1+e^{\beta_0+\beta_1}}$ | $1-\pi(0) = \frac{1}{1+e^{\beta_0}}$ |
| Total | 1.0 | 1.0 |

The odds of the outcome being present among individuals with $x$ = 1 is defined as $\frac{\pi(1)}{[1-\pi(1)]}$. Similarly, the odds of the outcome being present among individuals with $x$ = 0 is defined as $\frac{\pi(0)}{[1-\pi(0)]}$. The log of the odds, as defined previously, is called the logit and, in this case, these are:

$$g(1) = \ln\left\{\frac{\pi(1)}{[1-\pi(1)]}\right\} \qquad (9)$$

and

$$g(0) = \ln\left\{\frac{\pi(0)}{[1-\pi(0)]}\right\} \qquad (10)$$

The odds ratio, denoted by $\psi$, is defined as the ratio of the odds for $x$ = 1 to the odds for $x$ = 0, and is given by the eq. (11).

$$\psi = \frac{\frac{\pi(1)}{[1-\pi(1)]}}{\frac{\pi(0)}{[1-\pi(0)]}} \qquad (11)$$

The log of the odds ratio, termed log-odds ratio, or log-odds, is:

$$\ln(\psi) = \ln\left[\frac{\frac{\pi(1)}{[1-\pi(1)]}}{\frac{\pi(0)}{[1-\pi(0)]}}\right] = g(1) - g(0) \qquad (12)$$

Using the expressions for the logistic regression model shown in Table 1 and eq. 11 the odds ratio is:

$$\psi = \frac{\left(\frac{e^{\beta_0+\beta_1}}{1+e^{\beta_0+\beta_1}}\right)\left(1+e^{\beta_0+\beta_1}\right)}{\left(\frac{e^{\beta_0}}{1+e^{\beta_0}}\right)\left(1+e^{\beta_0}\right)} = \frac{e^{\beta_0+\beta_1}}{e^{\beta_0}} = e^{\beta_1} \Rightarrow \psi = e^{\beta_1} \qquad (13)$$

and the logit difference, or log odds, is

$$\ln(\psi) = \ln(e^{\beta_1}) = \beta_1 \qquad (14)$$

This fact concerning the interpretability of the coefficients is the fundamental reason why logistic regression has proven such a powerful analytical tool for epidemiology, health and ergonomics areas and it can also be applied in the field of production engineering.

The odds is a measure of association and has found wide use, as it approximates how much more likely (or unlikely) it is for the outcome to be present among those with $x$ = 1 than between those with $x$ = 0. (Breslow and Day, 1980, Schlesselman, 1982, Kelsey *et al.*, 1986, Rothman, 1986).

The interpretation given for the odds ratio is based on the fact that in many instances it approximates a quantity called the relative risk. This parameter can be represented by $\eta$ and is equal to the ratio $\frac{\pi(1)}{\pi(0)}$. It follows from eq. (10) that $\psi \approx \eta$ if $\frac{[1-\pi(0)]}{[1-\pi(1)]} \approx 1$. This approximation will hold when $\pi(x)$ is small for both $x$ = 1 and 0.

## 4. METHODOLOGY

The population in this study consisted of 60 bus drivers, male, ages between 24 and 57 years, working in one of the six urban public transportation concessionaries in the city of João Pessoa, Brazil for at least four years in this function. Due to the ethical considerations regarding such studies, the company involved did not permit their identification.

To evaluate the work ability, use was made of an auto-applicable questionnaire named Work Ability Index – WAI (Tuomi *et al.*, 1997), utilized for workers' health service. The work ability refers to the worker's capability in performing his duties and is graded according to the points system shown in Table 2. Along with the WAI, another questionnaire was applied, regarding aspects related to the bus drivers' perception to the thermal and noisy environment, to the work organization and to the population socio-demographic data.

Table 2: Work ability index classification

| **Points** | **Work Ability** |
|---|---|
| 7-27 | Poor |
| 28-36 | Moderate |
| 37-43 | Good |
| 44-49 | Excellent |

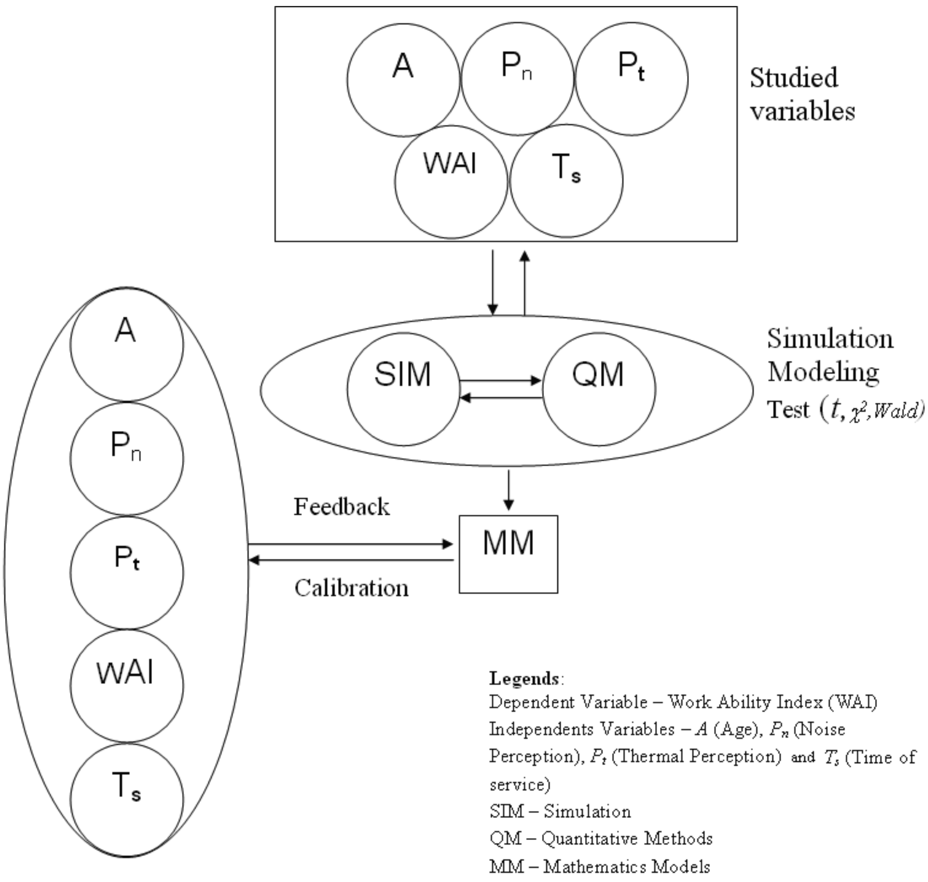


Figure 1: Methodology employed

A non-linear estimating logistic regression was applied in order to verify the relations between the independent variables (age ($A$), time of service as an urban bus driver ($T_s$) and perceptions about the thermal ($P_t$) and noise ($P_n$) environment and the dependent variable (WAI). The perception variables $P_n$ and $P_t$ were classified as: bad (1), regular (2), good (3) and excellent (4). The steps of the statistical analysis are shown in Fig. 1.

The DV $Y$ was transformed into a dummy variable for the logistics regression analysis. The cutoff point stipulated for $Y$ was: $36 < \text{WAI} \leq 49$, $Y = 0$ and $7 \leq \text{WAI} \leq 36$, $Y = 1$.

With an aim to evaluate the significance and consistence of the logistic regression models, the Chi-Square test and Wald's test were applied. The first is related to the model fitting information and likelihood ratio tests while the second is associated to the parameter estimates.

The softwares SPSS and STATISTICA were used as an experimental instrument for this research.

## 5. RESULTS

The sample's WAI varied from a minimum score of 28 minimum score to a maximum of 48. The WAI distributions for age and time of service are presented in Table 3.

Table 3: Work ability distribution for age and time of service categories.

| *Variable Category* | | *WAI* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Excellent | | Good | | Moderate | | Poor | | Total | |
| | | n° | % | n° | % | n° | % | n° | % | n° | % |
| Age | 24--\| 34 | 7 | 11.6 | 5 | 8.3 | 1 | 1.6 | 0 | 0 | 13 | 1.6 |
| | 35--\| 44 | 7 | 11.6 | 3 | 5 | 3 | 5 | 0 | 0 | 13 | 21.6 |
| | 45 or more | 7 | 11.6 | 3 | 5 | 24 | 40 | 0 | 0 | 34 | 56.6 |
| | Total | 21 | 35 | 11 | 18.3 | 28 | 46.6 | 0 | 0 | 60 | 100 |
| Time of service | 4 ---\| 10 | 14 | 23.3 | 7 | 11.6 | 3 | 5 | 0 | 0 | 24 | 40 |
| | 11---\| 17 | 1 | 1.6 | 0 | 0 | 7 | 11.6 | 0 | 0 | 8 | 3.3 |
| | 18 or more | 6 | 10 | 4 | 6.6 | 18 | 30 | 0 | 0 | 28 | 6.6 |
| | Total | 21 | 35 | 11 | 18.3 | 28 | 46.6 | 0 | 0 | 60 | 100 |

The results relating to perception that the bus drivers have about heat and noise of their work environment are shown in Table 4.

Table 4: Bus driver perception about the noisy and thermal environment.

| NOISE | | HEAT | |
|---|---|---|---|
| **Answer** | **%** | **Answer** | **%** |
| Poor | 35 | Poor | 38.3 |
| Moderate | 35 | Moderate | 35 |
| Good | 30 | Good | 26.6 |
| Excellent | 0 | Excellent | 0 |
| Total | 100 | Total | 100 |

The statistical analysis showed that the set of Independent Variables (IVs), that is, Thermal Perception ($P_t$), Noise Perception ($P_n$), Time of Service ($T_s$) and Age ($A$), together, has a relation with the DV, as recorded in Table 5. This statement is pertinent since the Chi-square value for the difference between the final and the intercept models is highly significant.

Table 5: Model Fitting Information (Pt, Pn, Ts and A as independent variables)

| Model | Model Fitting Criteria | Likelihood Ratio Tests | | |
|---|---|---|---|---|
| | -2 Log Likelihood | Chi-Square | df | Sig. |
| Intercept Only | 82.108 | | | |
| Final | 44.913 | 37.195 | 4 | 0.000 |

Table 6: Likelihood Ratio Tests (Pt, Pn, Ts and A as independent variables)

| Effect | Model Fitting Criteria | Likelihood Ratio Tests | | |
|---|---|---|---|---|
| | -2 Log Likelihood of Reduced Model | Chi-Square | df | Sig. |
| Intercept | 51.105 | 6.192 | 1 | 0.013 |
| $P_t$ | 49.848 | 4.935 | 1 | 0.026 |
| $P_n$ | 50.590 | 5.677 | 1 | 0.017 |
| $T_s$ | 44.915 | 0.002 | 1 | 0.968 |
| $A$ | 56.107 | 11.194 | 1 | 0.001 |

On the other hand, as shown in Table 6, the Chi-square values of $P_t$, $P_n$ and $A$ are significant while the same is not true with the variable $T_s$ (*Sig*. = 0.968 > $\alpha$ = 0.05). This shows a probable relationship between such variables and the WAI.

This affirmation can be confirmed by Wald's test. Analyzing the consistence of the parameters of the logistic regression model, presented in Table 7, it can be verified that only the variable $T_s$ is not consistent ($Sig$ = 0.968 > 0.05 = $\alpha$). A correlation analysis was done involving $T_s$ and each one of the remaining variables and it was observed that the Pearson's correlation coefficient ($R$) between $T_s$ and $A$ was 0.759. This value demonstrates a reasonable linear correlation between these variables and it might be a possible explanation for the inconsistency of $T_s$ in the current model. Therefore, only the variables $P_t$, $P_n$ and $A$ should be considered, requiring a re-evaluation of the relation between these variables and the WAI.

Table 7: Parameter Estimates (Pt, Pn, Ts and A as independent variables)

| | B | Std. Error | Wald | df | Sig. | Exp(B) | 95% Confidence Interval for Exp(B) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Lower Bound | Upper Bound |
| Intercept | -6.150 | 2.885 | 4.543 | 1 | 0.033 | | | |
| $P_t$ | -1.046 | 0.497 | 4.432 | 1 | 0.035 | 0.351 | 0.133 | 0.930 |
| $P_n$ | -1.029 | 0.460 | 5.006 | 1 | 0.025 | 0.357 | 0.145 | 0.880 |
| $T_s$ | -0.003 | 0.067 | 0.002 | 1 | 0.968 | 0.997 | 0.875 | 1.137 |
| $A$ | 0.221 | 0.077 | 8.184 | 1 | 0.004 | 1.247 | 0.221 | 0.077 |

However, in spite of the inconsistency of the variable $T_s$, Table 8 shows that all independent variables, jointly, have correctly classified the WAI in 85.0% of the cases. The 15.0% inappropriate classifications might be related to unevaluated variables, to the questionnaire elaboration, or even due to the subjective perception of each bus driver.

Since the variable $T_s$ appears to be inconsistent, it was removed from the analysis, and the relation between the variables $P_t$, $P_n$, $A$ and the dependent variable WAI was re-evaluated. Thus, from Table 9, it can be observed that difference between the final and intercept models is significantly high ($Sig.$ = 0.000 < $\alpha$ = 0.05). This would strongly indicate that these three variables have a considerable influence on the WAI.

Table 8: Classifications of the variable WAI (Pt, Pn, Ts and A as independent variables)

| Observed | Predicted | | |
|---|---|---|---|
| | 0.00 | 1,00 | Percent Correct |
| 0.00 | 22 | 4 | 84.6% |
| 1.00 | 5 | 29 | 85.3% |
| Overall Percentage | 45.0% | 55.0% | 85.0% |

Table 9: Model Fitting Information (Pt, Pn and A as independent variables)

| Model | Model Fitting Criteria | Likelihood Ratio Tests | | |
|---|---|---|---|---|
| | -2 Log Likelihood | Chi-Square | df | Sig. |
| Intercept Only | 75.176 | | | |
| Final | 37.983 | 37.193 | 3 | 0.000 |

Table 10: Likelihood Ratio Tests (Pt, Pn and A as independent variables)

| Effect | Model Fitting Criteria | Likelihood Ratio Tests | | |
|---|---|---|---|---|
| | -2 Log Likelihood of Reduced Model | Chi-Square | df | Sig. |
| Intercept | 44.741 | 6.758 | 1 | 0.009 |
| $P_t$ | 42.984 | 5.001 | 1 | 0.025 |
| $P_n$ | 43.683 | 5.700 | 1 | 0.017 |
| $A$ | 61.091 | 23.108 | 1 | 0.000 |

Table 11: Parameter Estimates (Pt, Pn and A as independent variables)

| | B | Std. Error | Wald | df | Sig. | Exp(B) | 95% Confidence Interval for Exp(B) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Lower Bound | Upper Bound |
| Intercept | -6.125 | 2.818 | 4.724 | 1 | 0.030 | | | |
| $P_t$ | -1.043 | 0.493 | 4.478 | 1 | 0.034 | 0.352 | 0.134 | 0.926 |
| $P_n$ | -1.027 | 0.458 | 5.027 | 1 | 0.025 | 0.358 | 0.146 | 0.879 |
| $A$ | 0.219 | 0.064 | 11.651 | 1 | 0.001 | 1.245 | 1.098 | 1.411 |

Table 10 shows that there is a strong relationship between each independent variable and the WAI, with $A$ being the most significant. This statement is ratified throughout the Wald's statistic as observed in Table 11.

After removing the variable $T_s$, the percentage of correct classifications (Table 12) has increased to 86.7%, a higher value if compared to the previous model (see Table 8).

Table 12: Classification of the WAI variable percentage (Pt, Pn and A as independent variables)

| Observed | Predicted | | |
|---|---|---|---|
| | 0.00 | 1.00 | Percent Correct |
| 0.00 | 23 | 3 | 88.5% |
| 1.00 | 5 | 29 | 85.3% |
| Overall Percentage | 46.7% | 53.3% | 86.7% |

From the data found in Table 11, the multiple logistic regression model, with $P_t$, $P_n$, $A$ as the IVs, can be expressed as follows:

$$Y = \frac{\exp(-6.125 - 1.043 \cdot P_t - 1.027 \cdot P_n + 0.219 \cdot A)}{1 + \exp(-6.125 - 1.043 \cdot P_t - 1.027 \cdot P_n + 0.219 \cdot A)} \qquad (15)$$

Finally, a simple logistic regression analysis was conducted considering only $A$ as the IV because it tends to be the most significant. As expected, the results exhibited in Tables 13 and 14 and 15 illustrate a strong significance of this variable. Table 16 shows that percentage of correct classifications was 78.3%.

In addition, it can be verified in Table 15 that the odds-ratio corresponds to 1.235 (from eq. (13), $\psi = e^{\hat{\beta}} = e^{0.211} = 1.235$). This means that when the bus driver's age increases by one unit, there is a 23.5% chance of his work ability falling to a range of poor to moderate ($Y$ = 1).

Table 13: Model Fitting Information (A as independent variable)

| Model | Model Fitting Criteria | Likelihood Ratio Tests | | |
|---|---|---|---|---|
| | -2 Log Likelihood | Chi-Square | df | Sig. |
| Intercept Only | 63.671 | | | |
| Final | 38.101 | 25.570 | 1 | 0.000 |

Table 14: Likelihood Ratio Tests (A as independent variable)

| Effect | Model Fitting Criteria | Likelihood Ratio Tests | | |
|---|---|---|---|---|
| | -2 Log Likelihood of Reduced Model | Chi-Square | df | Sig. |
| Intercept | 64.734 | 26.633 | 1 | 0.000 |
| *A* | 63.671 | 25.570 | 1 | 0.000 |

Table 15: Parameter Estimates (A as independent variable)

| | B | Std. Error | Wald | df | Sig. | Exp(B) | 95% Confidence Interval for Exp(B) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Lower Bound | Upper Bound |
| Intercept | -9.721 | 2.721 | 12.760 | 1 | 0.000 | | | |
| *A* | 0.211 | 0.058 | 13.160 | 1 | 0.000 | 1.235 | 1.102 | 1.384 |

Table 16: Classification of the WAI percentage (A as independent variable)

| Observed | Predicted | | |
|---|---|---|---|
| | 0.00 | 1.00 | Percent Correct |
| 0.00 | 21 | 5 | 80.8% |
| 1.00 | 8 | 26 | 76.5% |
| Overall Percentage | 48.3% | 51.7% | 78.3% |

According to the parameters observed in Table 15, the simple logistic regression model, with *A* as the IV, can be expressed as follows:

$$Y = \frac{\exp(-9.721 + 0.211 \cdot A)}{1 + \exp(-9.721 + 0.211 \cdot A)} \qquad (16)$$

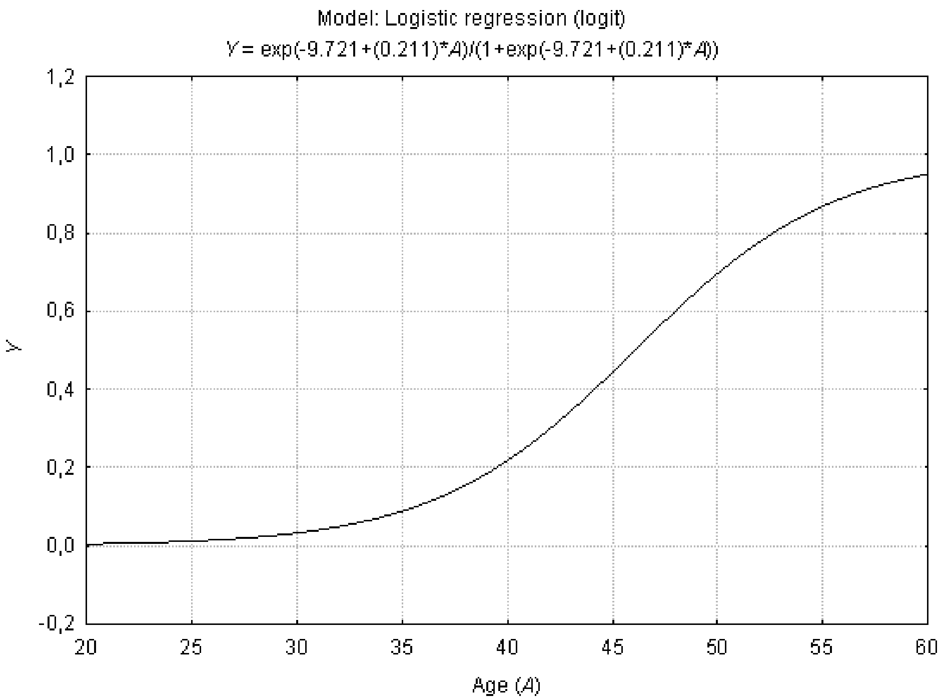


Figure 2: Logistic Function's Graph

The logistic function can be observed in Fig. 2. It can be verified that the value of *Y* tends to 1 (WAI's range of poor to moderate) when the age of the bus driver increases.

According to Carvalho Filho and Papaléo Neto (2000), the thermal-regulation process becomes precarious with aging, affecting the efficiency of this mechanism and decreasing the heat tolerance in elderly individuals. Therefore, the high levels of thermal discomfort related by the older bus drivers can be referred to the losses in the efficiency of thermoregulation determined by the aging process, which in consequence can contribute to the work ability deterioration of these professionals.

Carvalho Filho and Papaléo Neto (2000) and Kauffman (2001) state that sympathetic reflexes of stress, which can be liberated by hearing stimulation like noise, determined "flight and fight" systemic reactions in the organism as a whole. Such reactions can cause an increase in arterial blood pressure, raise in heart rate, mobilization of the body's energy reserves as well as changes in alertness. These are some of the stress symptoms.

When this stimulus does not cause an immediate harm, the organism goes through successive adaptation processes and recurrent stress state, which can take the person either to a chronic stress state, or to a stronger adaptation. However, with the natural decline of the organic functions caused by aging, these mood changes are not easily supported by the organism (Kauffman, 2001). This leads to a chronic fatigue state, decreasing the tolerance to a noisy environment and contributing to their work ability loss.

The organic functions deterioration caused by aging, can be another explanation for older people to show high levels of discomfort related to noise and heat, and, because of that, they have shown lesser work efficiency. However, as physiological variables were not evaluated in this study, these considerations should be analyzed in greater depth in order to get a consistent result about the effects of noise and heat on elderly people.

The studies performed by Bellusci and Fischer (1999) with forensic workers, and by Boldori (2002) with firemen, have found the same relation between WAI and age as the one verified in this study. Nevertheless, they disagree with the result found by Kloimueller *et al*. (2000), who have found a low association between this variable and the urban bus drivers work ability.

The relation between age and work ability can be explained as a result of the natural aging process, which in fact confirms that the WAI is not satisfactory all life long, demanding long range studies involving frequent workers' evaluation.

Thus, age and discomfort related to noise and heat are somehow associated with the loss of the work ability of the urban bus drivers of the population studied.

## 6. CONCLUSION

Logistic regression has proven such a powerful analytical tool for quantitative assessment in the fields of epidemiology, health and ergonomics areas and it can also be applied in Production Engineering as well. It has been very much used, not only because its theoretical functions are simpler, but, mainly, due to its simple interpretation as a logarithm of the chance rate (odds ratio).

This technique was used to evaluate the work ability of urban bus drivers of the city of João Pessoa, Brazil. The statistical analysis showed that elderly people have a greater probability of having a moderate or low WAI, i.e., as the age of bus drivers increases the work ability decreases. And also when greater the discomfort feeling due to noise and heat, higher is the bus drivers' probability of presenting a poor to moderate work ability.

In this way, the biggest probability of a bus driver to show a low or moderate WAI was presented by the elderly ones, who have presented bigger discomfort regarding the noise and heat variables. The time of service did not show a relation with the work ability. These statements can be explained by the physical changes occurring during the aging process, which decrease the individual tolerance to the exposure to these environmental stress factors.

The elderly people's low tolerance to stress reactions caused by the noise and the deterioration of the thermal regulation mechanisms, can be the explanation for their having high discomfort levels related to noise and heat, and consequently low work ability levels.

However, in spite of these signs, physiological variables were not included in this research, which is a limitation. Hence, an investigation of these variables is recommended in order to obtain consistent results about the influence of the thermal and noisy environment on aging people.

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# Multiproduct supply chain - Strategic planning and forecasting

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**Abstract**
The relation among the actor's of the Supply Chain defines its main characteristics, and therefore the Distribution and Manufacturing Strategy that the actors must follow in order to fulfill the Service Equation. In a Multiproduct Supply Chain, the different *Negotiating Force* of the different actors will truly influence in the final design on the Chain Configuration. Depending on which actor has more power, the Supply Chain must react to different supply policies. Forecasting Tools are presented as an option to predict the *product Distribution and Manufacturing needs* and as a way to counterbalance the different negotiating force among actors.

**Key words:** Logistics, Business Strategy, Forecast, Distribution & Multiproduct Manufacturing.

## INTRODUCTION

Today's world is becoming a global market with disappearing boundaries. Nowadays, one of the critical constraints for companies, are the accuracy of manufacturing, movement, and storage for the products along the Supply Chain, within the functions that make it possible to happen: according to Chopra *et al.* (2004) "distribution refers to the steps taken to move and store a product from the supplier stage to a customer stage in the Supply Chain". In order to have products moved and commercialized, the manufacturing function is needed along the Supply Chain since it works as the chain's *supplier*. According to Bowersox *et al*. (2002) "manufacturers add value by converting raw materials into consumer or industrial products", since manufacturing takes time in terms of production processes, *production lead times* tends to be longer than *distribution lead times* and so manufacturing processes are more forecast-dependent than distribution processes; in a MTP/MTS context (Make-to-Plan/ Make-to-Stock); see Bowersox *et al*. (2002)). Transportation, Distribution, Storage and Manufacturing Logistics play a critical role in the Service Equation: Delivery Time, Place, Quantity and Cost.

The relationship between the actors of the Supply Chain defines the Distribution and Manufacturing Strategy that the actors must follow. It is required then, to analyze the business characteristics and to determine which is the most convenient strategy to fulfill the Service Equation, and later on, materialize this strategy in the Company's logistic procedures in order to make it happen.

This paper is organized as follows: section 2 gives an overview of what we propose as a Basic Supply and Distribution Network model; in section 2.1 we propose an application of the Quantitative Forecasting Tools within this Basic Distribution Network; later on we propose the Multi-product Distribution Network model; in section 2.2 we propose an application for Qualitative and Quantitative Forecasting Methods in terms of the *"Method Category-Aggregation Level* Matrix*"* applied to a Manufacturing context; this matrix proposes an application of forecasting techniques for a Multiproduct Manufacturing environment, which consists in an integration of the Quantitative and Qualitative Forecasting methods and the different potential aggregation degrees of the products. In section 3 we propose a categorization of the different Negotiating Force scenarios between Customer and Supplier that must be taken into account in order to plan the Distribution and Manufacturing Strategy, to strategically deal with important customers. Section 4 proposes some final conclusions.

## STRATEGIC PLANNING FOR THE SUPPLY CHAIN NETWORK

Knowing the market and the environment where the business develops is an important step to define the Supply, Production, and Distribution Policies. There are many different kinds of Distribution Network configurations that have evolved during the years, depending on the nature of its Business and the power of its actors: suppliers, customers and market. In order to study these networks we propose to reduce this diversity and to study the simplest network. Once it has been studied, it will be possible to make conclusions and, later on, generalize them to the complexity of the entire Network. Let's propose the following Basic Supply and Distribution Network:

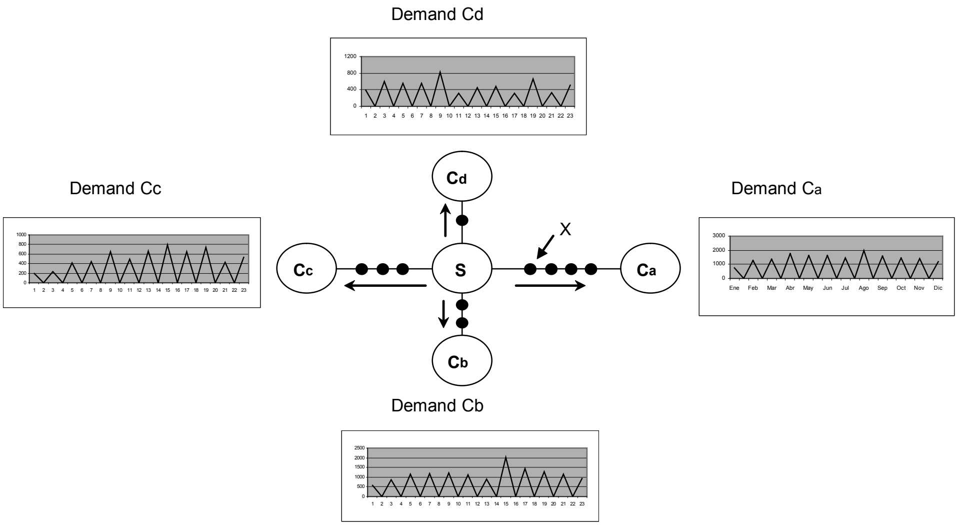


Figure 1. Basic Supply and Distribution Network and Demand Profile for each $C_i$

i. Let $C_i$ be the Customer who demands product from S. $C_i$ may have other demands confirmed by other(s) Customer(s) not showed in the drawing.
ii. Let S be the Supplier for $C_i$ (for i=a,b,c and d; the Basic Network could have *n* Customers).
iii. Let X be one Product that moves along the network according to $C_i$'s demand.
iv. Each $C_i$ is supplied of Product X exclusively by the Supplier S.
v. For each $C_i$, we have the recent historical Monthly Demand (sales curve). Demand behavior is similar for every $C_i$.
vi. Supplier S supplies uniquely its Product X to the Customers $C_i$'s. S has to work out the Production and Distribution Plan for Product X according to its customers needs.
vii. Suppose that transportation time is relatively short, so it is possible to approximate the Global Demand for S (in terms of time and quantity), as the sum of the individual demands in each $C_i$.
viii. Suppose that transportation cost is high, so transportation cost is very sensitive to freight consolidation.

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Now, which strategy must the Supplier S follow in order to create a Supply Policy for its Customers $C_i$? Are all its $C_i$ Customers asking for more product than needed? Can S trust this current sales data in order to make a global prediction? Is Supplier S pushing the product to its $C_i$'s so there will be big chances that global demand decreases because of overstocking at each $C_i$'s warehouse? How can the Manufacturer produce in order to supply according to the Distribution needs?

## DISTRIBUTION FORECASTING

Within the cooperation frame between enterprises categorized as S and C, it is very important to foster the mutual collaboration when building the Operations Plans: Demand Plan, Production Plan and the Distribution Plan. Relationships between non-collaborating enterprises show supply problems such as: product stockouts, overstocking, considerable forecasting errors, etc.

Many of these problems come from some companies' lack of cooperation and the differences in Negotiating Forces that exists among the actors in the network; differences that we will comment at the end of this publication. Based on a policy of mutual collaboration between S and C, how can a forecast be calculated in order to have a distribution plan (time and quantity) through a Basic Supply and Distribution Network? We propose to do this using Quantitative Forecasting Tools. Historical Demand data for Product X and four C's (four Customers) is showed in Figure #2.

| | | | | | | Sales History | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sales; Liters** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
| **Year 2003** | | | | | | | | | | | | |
| **Item** | Real | Real | Real | Real | Real | Real | Real | Real | Real | Real | Real | Real |
| Customer A | 766 | 1,279.68 | 1,363 | 1,784.70 | 1,646 | 1,641.74 | 1,460 | 2,005.26 | 1,610 | 1,437.45 | 1,399 | 1,204.60 |
| Customer B | 575 | 863.04 | 1,153 | 1,189.80 | 1,213 | 1,106.39 | 904 | 2,005.26 | 1,449 | 1,273.17 | 1,166 | 919.30 |
| Customer C | 192 | 238.08 | 419 | 436.26 | 650 | 499.66 | 661 | 791.55 | 644 | 739.26 | 433 | 538.90 |
| Customer D | 383 | 595.20 | 559 | 555.24 | 823 | 321.21 | 452 | 474.93 | 322 | 657.12 | 333 | 507.20 |
| **total** | **1,916** | **2,976** | **3,495** | **3,966** | **4,332** | **3,569** | **3,477** | **5,277** | **4,024** | **4,107** | **3,332** | **3,170** |
| **Year 2004** | | | | | | | | | | | | |
| | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
| | Real | Real | Real | Real | Real | Real | Real | Real | Real | Real | Real | Real |
| Customer A | 1,444 | 1,534 | 2,253 | 2,351 | 1,755 | 2,439 | 2,087 | 2,050 | 2,675 | 1,685 | 2,370 | 1,807 |
| Customer B | 1,083 | 1,035 | 1,907 | 1,568 | 1,293 | 1,644 | 1,292 | 2,050 | 2,408 | 1,492 | 1,975 | 1,379 |
| Customer C | 361 | 285 | 693 | 575 | 693 | 742 | 944 | 809 | 1,070 | 867 | 733 | 809 |
| Customer D | 722 | 714 | 924 | 732 | 877 | 477 | 646 | 486 | 535 | 770 | 564 | 761 |
| **total** | **3,611** | **3,568** | **5,778** | **5,225** | **4,618** | **5,303** | **4,968** | **5,395** | **6,688** | **4,814** | **5,642** | **4,756** |
| **Year 2005** | | | | | | | | | | | | |
| | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
| | Real | Real | Real | Real | Real | Real | Real | | | | | |
| Customer A | 1,470 | 2,536 | 3,208 | 3,166 | 3,062 | 3,057 | 2,898 | | | | | |
| Customer B | 1,103 | 1,710 | 2,714 | 2,111 | 2,256 | 2,060 | 1,794 | | | | | |
| Customer C | 368 | 472 | 987 | 774 | 1,209 | 930 | 1,311 | | | | | |
| Customer D | 735 | 1,180 | 1,316 | 985 | 1,531 | 598 | 897 | | | | | |
| **total** | **3,676** | **5,898** | **8,225** | **7,035** | **8,058** | **6,646** | **6,900** | | | | | |

Figure 2. Basic Supply and Distribution Network. $C_i$ Sales/Demand History for S

In order to forecast demand, we can use several well-known Quantitative Forecasting Methods: Moving Average, Simple Exponential Smoothing, Trend Corrected Exponential Smoothing (Holt's Model), Trend and Seasonality Corrected Exponential Smoothing (Winter's Model) and the Static Method, among the most popular forecasting methods according to Chopra *et al*. (2004). It is not an objective of this article to explain the algorithm of each forecasting method, but to set a guideline of an application of these methods in a Distribution context.

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Following the Model showed in Figure #1, and calculating the Forecast for the Global Demand according to data showed in Figure #2, we can see the results in the following comparative chart. For each of the Forecasting Methods we have compared the most common Forecast Evaluating Measures (Error, Absolute Error, MAD (Mean Absolute Deviation), and MAPE (Mean Absolute Percentage Error)). Based on this, is possible to evaluate the convenience of choosing one method (see Figure #3).

**Summary Table**
**Forecasting Effectiveness Indicators**

| Method | MAD<br>Mean Absolute Deviation | MAPE<br>Absolute Percentage | TSt<br>Tracking Signal | |
|---|---|---|---|---|
| Moving Average | 896 | 17 | -11,29 | -0,22 |
| Simple Exponential Smoothing | 1063 | 24 | -9,37 | 11,07 |
| Trend Corrected Exponential Smoothing (Holt's Model) | 760 | 17 | -3,78 | 5,19 |
| Trend and Seasonality Corrected Exponential Smoothing (Winter's Model) | 411 | 9 | -3,62 | 5,90 |
| Static Method | 372 | 8 | -3,91 | 5,27 |

Figure 3. Forecast Evaluating Measures for the Global Demand Forecast.

The best MAPE (8% in this case) is related to the Static Method. The second best MAPE is related to the Winter's Method which shows 9%. When analyzing the MAD, the best values are related to the Static and the Winter Method with 372 and 411 units. Simple Exponential Smoothing method yields a variation (1063 units) that exceeds the double of the variation related to the Winter's Model. MAD is related to the random component of the demand, so, the bigger the MAD, the forecast for the real demand becomes more variable. According to Chopra *et al.* (2004) "the MAD can be used to estimate the standard deviation of the random component assuming that the random component is normally distributed".

The Holt's, the Winter's and the Static methods show the steadiest Tracking Signal values. Tracking Signals measure the consistency of the method according to its capacity to not to bias its predictions. One biased prediction can consistently over or underestimate demand; the normal bias will fluctuate around zero since it will be random; please refer to Chopra *et al.* (2004).

In this case, either the Static Method or the Winter's Method would be chosen over the others methods. The convenience of using the Winter's Method rather than the Static Model is that Winter's has a dynamic characteristic, since this method takes into account the evolution of new demand and changes the Method's parameters (Level, Tendency and Seasonality Factors). On the other hand, the Static Method does not change; the parameters of the initial calculations are used until the initial calculation is run once again. Winter's Method (because of its self-changing properties) is convenient for multiproducts environments (since many different products can be forecasted without having to recalculate the parameters each time).

It is also possible to calculate an individual forecast for each network's node; the same Winter's analysis could be done for each $C_i$ node. It is up to the analyst to set the

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convenience of the aggregation level for the forecasting, since for many cases it would be important to calculate the forecast for all the nodes as a big node, and in other cases it would be important to calculate each node's forecast (for example, if it is the case of a Distribution Center that supplies all nodes, it is useful to calculate the forecast for the four nodes as a big node since we want to forecast the demand that will be allocated to this Distribution Center; later on we will distribute product to each node). Decision must be based on the real network's features and the possibility to postpone Distribution based on pull requirements and transportation feasibility.

Please refer to the next figure #4 Winter's Method Evaluation for $C_a$ node showing the Winter's calculations for this node. Same calculations should be done when forecasting $C_b$, $C_c$ and $C_d$ demands.

**Trend and Seasonality Corrected Exponential Smoothing (Winter`s Model)**

Alfa= 0.05 Beta= 0.1 Gama= 0.1

| year | month | period | demand Dt | Level Lt | Trend Tt | Seasonal Factor, St | Forecast, Ft | Error, Et | Absolute error, At | Mean Squared Error, MSEt | MADt | %Error | MAPEt | Tracking Signal TSt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | | 1090 | 52 | | | | | | | | | |
| 2003 | 1 | 1 | 766.4 | 1140 | 52 | 0.70 | 800 | 34 | 34 | 1125 | 34 | 4 | 4.38 | 1.00 |
| 2003 | 2 | 2 | 1279.68 | 1198 | 53 | 0.98 | 1172 | -108 | 108 | 6386 | 71 | 8 | 6.41 | -1.05 |
| 2003 | 3 | 3 | 1363.05 | 1245 | 52 | 1.19 | 1491 | 128 | 128 | 9713 | 90 | 9 | 7.40 | 0.60 |
| 2003 | 4 | 4 | 1784.7 | 1302 | 53 | 1.28 | 1657 | -127 | 127 | 11341 | 99 | 7 | 7.33 | -0.74 |
| 2003 | 5 | 5 | 1646.16 | 1362 | 53 | 1.09 | 1481 | -165 | 165 | 14545 | 112 | 10 | 7.88 | -2.13 |
| 2003 | 6 | 6 | 1641.74 | 1415 | 53 | 1.17 | 1661 | 19 | 19 | 12182 | 97 | 1 | 6.76 | -2.27 |
| 2003 | 7 | 7 | 1460.34 | 1466 | 53 | 1.02 | 1504 | 43 | 43 | 10710 | 89 | 3 | 6.22 | -1.98 |
| 2003 | 8 | 8 | 2005.26 | 1530 | 54 | 1.14 | 1738 | -267 | 267 | 18281 | 111 | 13 | 7.10 | -3.98 |
| 2003 | 9 | 9 | 1609.6 | 1577 | 53 | 1.13 | 1786 | 176 | 176 | 19696 | 119 | 11 | 7.53 | -2.26 |
| 2003 | 10 | 10 | 1437.45 | 1636 | 54 | 0.82 | 1339 | -98 | 98 | 18689 | 117 | 7 | 7.46 | -3.14 |
| 2003 | 11 | 11 | 1399.44 | 1680 | 53 | 0.94 | 1584 | 184 | 184 | 20072 | 123 | 13 | 7.98 | -1.48 |
| 2003 | 12 | 12 | 1204.6 | 1728 | 53 | 0.74 | 1276 | 71 | 71 | 18821 | 118 | 6 | 7.81 | -0.93 |
| 2004 | 1 | 13 | 1444.4 | 1795 | 54 | 0.70 | 1242 | -203 | 203 | 20530 | 125 | 14 | 8.28 | -2.51 |
| 2004 | 2 | 14 | 1534.24 | 1834 | 52 | 0.99 | 1833 | 299 | 299 | 25458 | 137 | 20 | 9.08 | -0.10 |
| 2004 | 3 | 15 | 2253.42 | 1888 | 53 | 1.18 | 2232 | -22 | 22 | 23792 | 130 | 1 | 8.54 | -0.28 |
| 2004 | 4 | 16 | 2351.25 | 1935 | 52 | 1.29 | 2497 | 146 | 146 | 23639 | 131 | 6 | 8.40 | 0.84 |
| 2004 | 5 | 17 | 1754.84 | 1967 | 50 | 1.10 | 2195 | 440 | 440 | 33624 | 149 | 25 | 9.38 | 3.69 |
| 2004 | 6 | 18 | 2439.38 | 2020 | 50 | 1.17 | 2364 | -76 | 76 | 32073 | 145 | 3 | 9.03 | 3.28 |
| 2004 | 7 | 19 | 2086.56 | 2069 | 50 | 1.02 | 2115 | 28 | 28 | 30428 | 139 | 1 | 8.63 | 3.63 |
| 2004 | 8 | 20 | 2050.1 | 2101 | 48 | 1.16 | 2461 | 410 | 410 | 37329 | 152 | 20 | 9.20 | 6.00 |
| 2004 | 9 | 21 | 2675.2 | 2162 | 50 | 1.12 | 2400 | -275 | 275 | 39161 | 158 | 10 | 9.25 | 4.04 |
| 2004 | 10 | 22 | 1684.9 | 2203 | 49 | 0.83 | 1830 | 145 | 145 | 38335 | 158 | 9 | 9.22 | 4.97 |
| 2004 | 11 | 23 | 2369.64 | 2267 | 50 | 0.93 | 2086 | -283 | 283 | 40156 | 163 | 12 | 9.34 | 3.07 |
| 2004 | 12 | 24 | 1807.28 | 2325 | 51 | 0.73 | 1697 | -111 | 111 | 38993 | 161 | 6 | 9.20 | 2.42 |
| 2005 | 1 | 25 | 1470.4 | 2361 | 50 | 0.71 | 1682 | 212 | 212 | 39228 | 163 | 14 | 9.41 | 3.69 |
| 2005 | 2 | 26 | 2536.14 | 2420 | 50 | 0.98 | 2352 | -184 | 184 | 39018 | 164 | 7 | 9.33 | 2.55 |
| 2005 | 3 | 27 | 3207.75 | 2482 | 52 | 1.18 | 2925 | -283 | 283 | 40544 | 168 | 9 | 9.31 | 0.80 |
| 2005 | 4 | 28 | 3165.75 | 2531 | 51 | 1.28 | 3243 | 78 | 78 | 39311 | 165 | 2 | 9.06 | 1.28 |
| 2005 | 5 | 29 | 3062.04 | 2595 | 53 | 1.08 | 2798 | -264 | 264 | 40359 | 168 | 9 | 9.05 | -0.31 |
| 2005 | 6 | 30 | 3057.16 | 2645 | 52 | 1.18 | 3112 | 55 | 55 | 39116 | 164 | 2 | 8.81 | 0.02 |
| 2005 | 7 | 31 | 2898 | 2704 | 53 | 1.02 | 2752 | -146 | 146 | 38540 | 164 | 5 | 8.69 | -0.87 |

Forecast Equation Ft+l = (Lt + lTt) * S t+l

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | 8 | 32 | | | | 1.14 | 3151 |
| 2 | 9 | 33 | | | | 1.13 | 3172 |
| 3 | 10 | 34 | | | | 0.82 | 2351 |
| 4 | 11 | 35 | | | | 0.94 | 2737 |
| 5 | 12 | 36 | | | | 0.74 | 2188 |

| | *Coeficients* |
|---|---|
| Interception | 1090.32 |
| Variable X 1 | 52.266 |

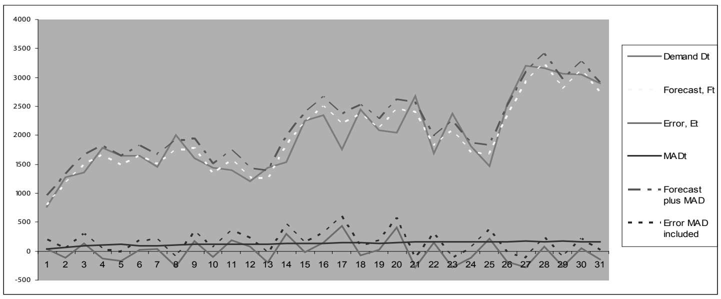


Figure 4. Winter's Method Evaluation for $C_a$ node

Some remarks related to figure #4 are:

- We propose the use of the graphic tool as a way to display and, therefore, understand the effectiveness of the forecasting method along recent historic data.
- Negative Forecast Error represents stockouts (when the forecasted line is below the demand line this represent a stockout); positive Forecast Error is related to overstocking.
- Using MAD, it is possible to estimate the standard deviation of the demand's random component. Using this criterion, it is possible to set a policy of *Safety Inventory*, due to the fact that if we add a MAD factor to the Forecast, it is possible to reduce the possible stockouts using higher inventory level at each node; also a global Safety Inventory can be set in S and "*Pull*" according to each node's requirements.
- The *Forecast plus MAD* line (semi-continuous green line) is exactly the same line that the yellow one (Forecast Line); note that the difference is that *Forecast Plus MAD* line has been moved up by adding a 1.0 MAD factor to the forecasted values. The standard deviation on the demand's random component is considered to be 1.25MAD, so this Safety Inventory is related to a protection of less than a standard deviation. We propose that this level should be set qualitatively by the analyst according to the Supply Chain's inherent characteristics.

Using this criterion, it is possible to set the Safety Inventory of the Distribution Plan. Now, it is important to define policies regarding where to keep this Safety Inventory: Should we keep it at each node? Should we aggregate it in a strategic node and pull it according to current demand evolution? The answer to these questions lies within each Strategic Network case and the *postponement* possibilities.

The following figure shows a summary of the Distribution Forecast for August, September, October and November. The Winter's Forecast shown is not altered with any MAD protection factor. This forecast application allows the company's analyst to calculate the Supply Chain's forecast for all the items that must be Distributed along the network's nodes.

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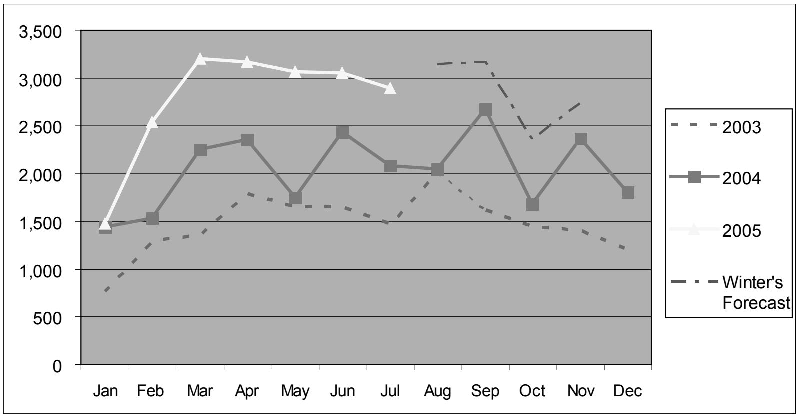


Figure 5. Basic Distribution Network. Winter's Method Forecast for $C_a$ node.

Another important remark regarding the Simple Distribution Network, is that Forecast can help to define the *Pull-Push* Distribution boundary. In this case, the Push Method can be used to send product to each node according to the forecasted needs (since this demand has some degree of certainty and this allows to profit from the Transportation Economy of Scale). Pull Methods can be used to handle the uncertainty demand (MAD) and pull stock from other nodes. Increasing the forecasting effectiveness for each node minimizes overstocking in certain nodes and stockouts in others, since product allocation within the Basic Distribution Network will be more effective.

Using the Basic Distribution Network as a basis, we can jump into conclusions when analyzing Multiproduct Distribution Networks. Multiproduct Distribution Networks are similar to the Basic Network but its configurations change since S supplies different products (x,y,z,...n) to each one of its $C_i$'s, which makes Networks much more complex. Please refer to figure #6. When forecasting the Multiproduct Network, it is possible to use the same forecasting procedure already presented; but when planning the Transportation Plan, it is important to take into account that Transportation now should consolidate different products fostering the economy of scale of the trip.

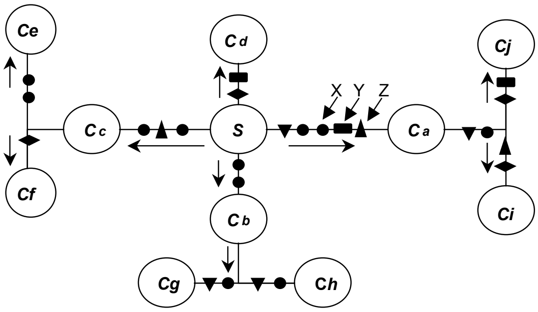


Figure 6. Multiproduct Distribution Network.

The Strategic Planning for a Multiproduct Distribution Network is much more complicated since this Network has to take into account Multi-Relationships among the multiples Si and Ci and different products (x,y,z,...n). At the same time, these $S_i$ actors play the $C_i$ roll for other actors and vice-versa. These relations will be discussed later.

Quantitative Forecasting methods are not enough for Multiproduct Networks. Qualitative Methods can improve the Forecast efficiency since they include predictions based on expected future facts (as per Carranza (2004), it is necessary to use *forward information*) not included in the historic information, for example: new markets or customers. The Qualitative and Quantitative Methods interaction will be presented in the Manufacturing application that follows; a future study branch will be how to integrate the Qualitative Methods in the Distribution context.

## MANUFACTURING FORECASTING

Quantitative Methods can be automated, since it is possible to use computers to work out the Forecast for many products. Qualitative Methods are more difficult to implement since the expert criterion should be heard and this is a time-intensive process. Another important factor to consider when forecasting is the aggregation level, since it is easy to work out a Quantitative Method for a SKU (Stock Keeping Unit) level, but it is almost impossible to do so using a Qualitative Method (because of the large quantity of SKU's in the multiproduct scenario, which results very difficult for humans to manage). Nevertheless, the expert criterion is easy to take into account for a higher aggregation level (family level, market level, etc...). According to Bowersox *et al* (2002) and Frazelle (2002), it is important to integrate and rationalize top-down and bottom-up forecasts with human intelligence. During our application in the Distribution context, we have realized the importance of considering "qualitative input". For this reason, we have included this consideration within the Manufacturing context.

Manufacturing is the Supply Chain's source; it feeds product to the chain and makes possible the Distribution process afterwards. Manufacturing increasingly faces the product proliferation phenomenon in terms of demand and product diversity. This proliferation has made difficult to match the product's supply and demand, especially since factors such as strict customer needs, lead time reductions requirements, life cycle reductions, globalization and obsolescence risk increase due to emerging technologies and competition proliferation that have made this match harder than ever. Since Manufacturing is the Supply Chain's source, it has to be strictly planned in order to guarantee product availability along the Chain.

Some techniques have already been developed in order to counterbalance this proliferation phenomenon; among the most popular we have "manufacturing postponement" and "logistics postponement", as per Bowersox *et al.* (2002). These techniques are based on *"Pull"* principles. Nevertheless, most of the companies feel the environment's pressure in terms of a great dependence of *Push Manufacturing Strategies* (MTP/MTS for example; please note that all Manufacturing Strategies, even MTO or ATO[1] have certain degree of *Push Manufacturing*; as is the case of components procuring) since there is a need to promptly fulfill customer needs and therefore, speculative (forecasted) needs have to be considered in advance in order to manufacture products prior to customer orders (when it is not possible to attain a flexible and capable manufacturing system). This *Push Manufacturing* dependence makes the precision of the Forecasting Process even more critical.

## MULTIPRODUCT FORECASTING CALCULATION COMPLEXITY

The complexity of Multiproduct Forecasting calculations relies on internal and external factors. Among such internal factors we could highlight: large quantity of items (SKU's), a big pool of clients, a lot of different family products, new products coming out everyday, products with correlated demand, complementary products, high obsolescence rate due to product characteristics and nature, and so on. All these factors and other manufacturing dynamics must be taken into consideration when the analysts make forecast calculations for each SKU.

At the same time, analysts must take into consideration external factors such as: changing markets, sales risk increases, market expansions, demand oscillations, higher product obsolescence rate due to new technologies, the proliferation of competition, etc. All these factors must be taken into account in the Forecasting Process, especially through the use of Qualitative Methods.

We propose to integrate internal factors and external factors at the same time. A rich source with basic information could be historical sales data; in this data we can find the historic internal factors' interaction and the real demand that the company has faced. Through the study of this data, it is possible to calculate (for each SKU) the demand components such as *Level*, *Seasonality* and *Trend*; using the same analysis that we have already done in the Distribution case. This analysis or technique, also known as "back-casting", as stated by Frazelle (2002), allows us to calculate forecasts using several quantitative methods and then compare its capabilities to predict the demand's pattern in order to choose the best method. Usually this technique is easy to automate since quantitative methods are composed by mathematics calculations. This feature makes "back-casting" a possible method to be used in a multiproduct context since it is easy to calculate forecasts for a lot of SKU's using computational resources. Nevertheless, this method is based on the assumption that future sales behavior could be predicted based on historic sales; in this case, it is understood that the internal and external conditions will be the same in the future, so they will be likely to repeat

[1] MTO or Make-to-Order; ATO or Assembled-to-Order.

themselves and so, we could forecast future relying on the past. This assumption is not totally valid, since it is very likely that conditions will change because of the market and company's dynamics; as is the case of political variables as per Carranza (2004).

This constraint has made us consider the need to incorporate to the forecast calculations factors that could change future demand. Several authors agree with this and state that "in order to improve the forecasts, it is important to obtain forward information" as could read the translation of what Carranza (2004) has stated. In order to attain this integration, we propose to integrate the Quantitative and the Qualitative Methods in their convenient aggregation level.

## QUANTITATIVE METHODS

As previously commented, Quantitative Methods decrease calculations times and their complexity in a Multiproduct context. As presented in the Distribution case, we will use five of the most used methods, and we will judge their prediction capability for each product demand pattern based on the measures of forecasting error already presented; please refer to section 2.1 Distribution Forecasting.

We propose to use the Quantitative Methods in a Low Aggregation Level. Low Aggregation Level has to be define for each SKU; we propose to aggregate the SKU's in the lower but convenient aggregation level; for example we can aggregate SKU's in small families that includes similar or related SKU's, or we could aggregate single SKU's (which would be seen as one-member family). We propose to use Quantitative Methods to profit from the historic data related to each low aggregation level and the possibility of individual calculations; we propose to chose the best method that forecasts the product's demand; as is the case of the following figure which present a coordinate for Winter's or Holt's Method as the chosen method for a certain SKU aggregation level. After all calculations have been completed for all SKU's, all these results are considered together as one coordinate (SKU aggregated). Note that Quantitative Methods could be used in Higher Aggregation Levels, but we propose to use them in Low Levels; see next figure.

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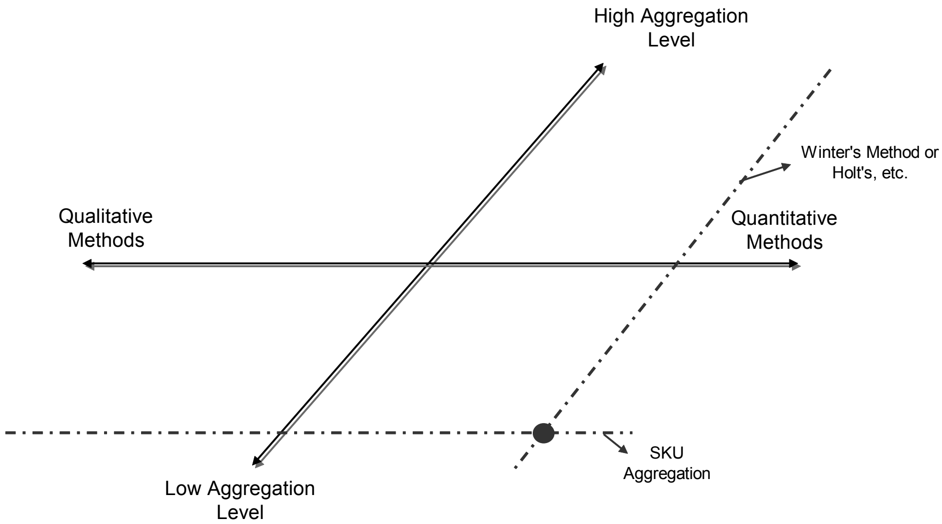


Figure 7. Quantitative Methods and Low Aggregation Level in the "*Method Category-Aggregation Level* Matrix".

## QUALITATIVE METHODS

Within the "*Method Category-Aggregation Level* Matrix", we propose to incorporate subjective variables to the forecast calculations at Higher Aggregation Levels. The subjective factors that are incorporated through Qualitative Methods include the manager's intuition (intuition developed based on the manager's experience and "know-how"), previous knowledge of variables that will affect the demand's level (for example: temporary offers, temporary product importation that will compete with the company's products, future market conditions, etc.), and others.

Expert criterion allows the analyst to incorporate his intuition into the forecast in a subjective manner for future demand. This criteria incorporates factors that will affect the future and that perhaps have not impacted sales during historic sales, therefore it permits to consider trends that would not be taken into account by the Quantitative Methods, which base their decision only on historic data. Among the most popular Qualitative Methods, we can highlight the following: a. Opinion Jury, b. Commercial Personnel Proposition, c. Delphi's Method, d. Market Research, and others as presented in Heizer *et al.* (2001).

Within a Multiproduct Manufacturing frame, it is more feasible to consider the expert's criteria in Higher Aggregation Levels and in monetary terms (revenues). It is very difficult for a Sales Department or for a Manager to estimate a forecast with certainty for every single SKU. Nevertheless, when forecasting SKU groups or even product families, qualitative forecasting is easier and precise. For example, it is easier for a Sales Manager to estimate global sales of 4 million dollars and it is very likely that this forecast become precise since the expert knows his company's sales behavior; his expert knowledge allows him to jump into subjective predictions related to multiples variables and factors. These predictions are truly difficult to obtain via mathematical models and its numerous relations that are hard to represent and justify mathematically speaking (especially since it represents complicated and time-consuming tasks). As commented by Silver (1985) there is a relationship between the method that has been used and the aggregation level; expert criteria is essential for the aggregated midterm forecasts. The following figure shows the two coordinates presented at the moment, as is the case for Qualitative Methods which are showed in High Aggregation Levels (Global Aggregation).

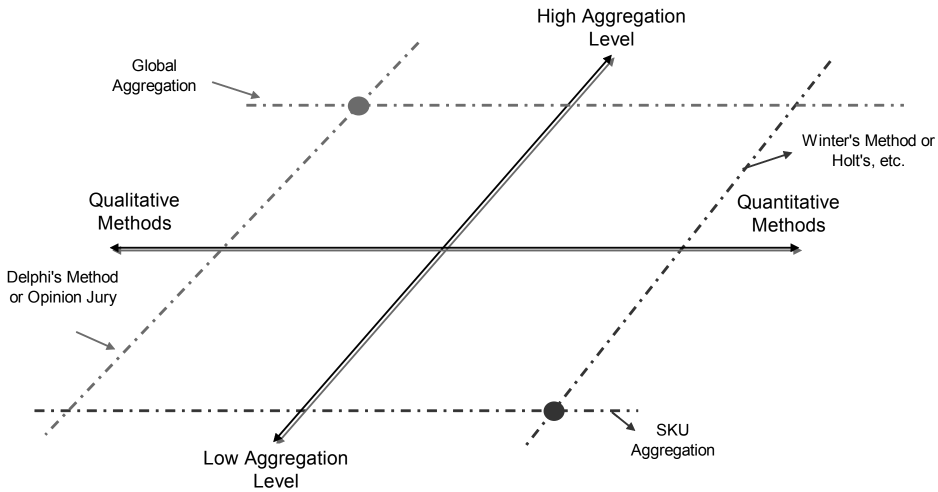


Figure 8. Qualitative Methods and High Aggregation Level in the "*Method Category-Aggregation Level* Matrix".

**INTEGRATION OF QUANTITATIVE AND QUALITATIVE METHODS**

In figures 7 and 8, we can recognize the coordinate "method category-aggregation level" concept within the matrix. Each of these coordinates suggests that each method is convenient to be used at a certain aggregation level; convenience that we have already discussed in terms of precision and calculation feasibility. This concept allows us consider the possibility of playing with several coordinates and integrate its results in order to achieve better forecasts. In this case, we propose to profit from the different advantages regarding each one of the coordinates and integrate them.

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In order to conceptualize this integration, we propose to create the "Integration Constant Axis (Φ)" in the matrix; this axis integrates the two coordinates. The "Integration Constant Axis (Φ)" presents the infinite possible integration combinations between these two coordinates; please refer to the next figure.

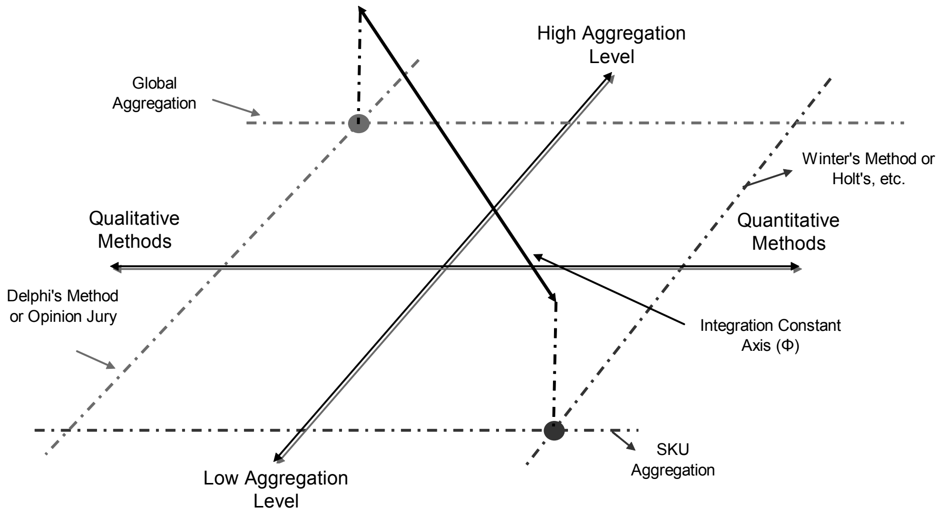


Figure 9. "*Method Category-Aggregation Level* Matrix" and the "*Integration Constant Axis* (Φ)".

Once the "Integration Constant Axis (Φ)" is drawn, it is necessary then to determine the constant value that better integrates both coordinates. When defining Φ we propose to use qualitative criteria using the expert opinion regarding the economic context where the company lies; the more stable the market is (this is the more stable the historic data is and the more it is expected to be in the future), the more reliable the model should be to the quantitative coordinate, since quantitative is based on the historic; the more unstable the market is, the more reliable the model should be to the qualitative coordinate; Φ should be biased accordingly. We also propose to qualitatively modulate Φ based on the results of the calculated forecast; In other words, based on the calculations result, we propose to validate the chosen Φ's value. We can see a potential Φ's value in the next figure.

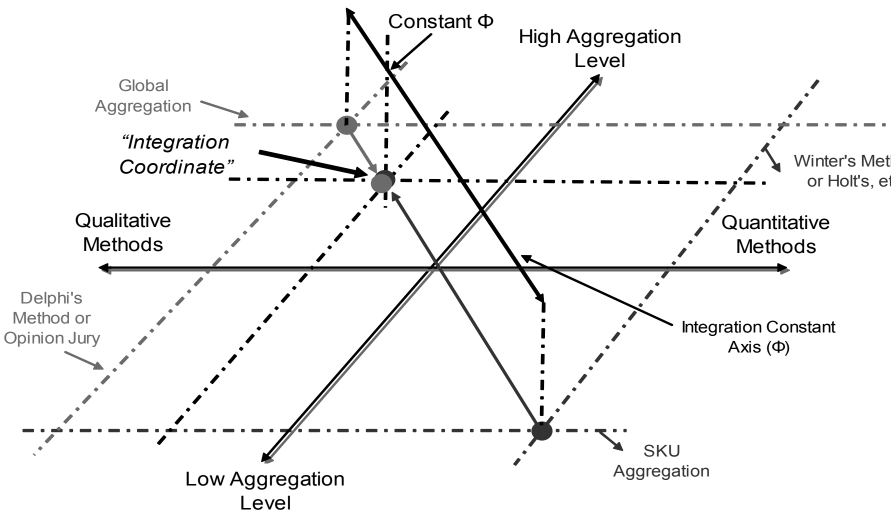


Figure 10. "*Method Category-Aggregation Level* Matrix" and the *Constant* Value (Φ)".

Note that this integration ends up with a new coordinate, the "Integration Coordinate". This new coordinate represents a new forecast that is formed by a new component along the Aggregation Level Axis and a new component along the Category Method Axis. In practice, this concept is quite interesting since it is possible to profit from the Qualitative Methods calculation easiness (in low aggregation levels) and to integrate the results of Qualitative Methods (in high aggregation levels and in terms of revenues/sales). This concept allows us to integrate the Top-Down and Bottom-Up concepts as Frazelle (2002) suggests. As stated by Bowersox (2002), Bottom-Up methods develops SKU forecasts and then builds them into an aggregation demand projection; The Top-Down approach develops a global forecast and then spreads the volume at a SKU level based on historical patterns.

## PROPOSED CALCULATION ALGORITHM

Based on the conceptual frame already presented, we present a calculation algorithm.

## BOTTOM UP CALCULATION

As already discussed, the low aggregation levels will be defined in terms of "SKU families" or $F_{sku}$'s; $F_{sku}$'s should be chosen based on criteria such as complementary products (products that complements each other in terms of demand), demand correlation, demand substitution, and the convenience of aggregating products in order to improve forecast's precision and calculation easiness. $F_{sku}$'s could include several SKU's or even be composed of a single SKU. The general idea is to determine little families, that because of product similarities, it is convenient to aggregate in a single family. For example, in the case of a forecasting process for a Supermarket, it is convenient to calculate as a family the forecast for products with similar behavior such as is the example of sodas; in this case we can get a global forecast and later on decompose it according to the historic data sales percentage of each soda brand. In this case, we use aggregated forecast to counterbalance the fact that certain customers search to buy one *soda*, and that it could be any of his preferred brands (product substitution; complementary products). Determining $F_{sku}$'s is still considered as a low aggregation level, since if we compare an $F_{sku}$'s within the multiproduct context, we realize that this aggregation is small if we compare it with the total SKU's quantity in the multiproduct context.

Once we have defined the $F_{sku}$'s we "back-cast" the forecast (as we did in the Distribution case showed in this article). We will have the Quantitative Method that adjusts the best to each $F_{sku}$ demand's pattern, this will allow us to find the best forecast for each $F_{sku}$ (we propose to call this forecast $FOR_{Fsku}$). Once $FOR_{Fsku}$ has been calculated we will decompose it accordingly for each SKU. In this case, this decomposition will be based on the SKU's historic weight or historic percentage within the SKU family ($F_{sku}$). In order to do this calculation we propose the following formula:

$$wf_{sku} = \frac{\sum D_{sku}}{(\sum D_t)} \qquad [1]$$

where:
$wf_{sku}$: SKU's demand weight factor within the SKU family ($F_{sku}$).
$D_{sku}$: SKU's historic demand.
$D_t$: SKU family's ($F_{sku}$) total demand.

Once we have calculated every $wf_{sku}$ we calculate the forecast for each SKU (we propose to call it $FOR_{sku}$) with the following formula:

$$FOR_{sku} = FOR_{Fsku} \cdot wf_{sku} \qquad [2]$$

where:
$FOR_{sku}$: individual SKU forecast.
$FOR_{Fsku}$: SKU family's ($F_{sku}$) forecast.
$wf_{sku}$: SKU's demand weight factor within the SKU family ($F_{sku}$).

In this moment we have the forecast ($FOR_{sku}$) for each SKU that composes the SKU family ($F_{sku}$). This procedure that we have already presented has to be done for each SKU that is manufactured in the company. In the case of new products (new SKU's), in which no historical data is available, $FOR_{sku}$ will be calculated using the most convenient method (for example: through a qualitative method or simply extrapolate a forecast from an existing similar product). This calculation will be not presented here and will be considered as a future investigation to incorporate in our model.

Once we have all the $FOR_{sku}$'s we calculate the monetary aggregation of these forecasts; we will call this aggregation $AFOR_{sku}$ (SKU's Forecasts Aggregation). $AFOR_{sku}$'s calculation follows this formula:

$$AFOR_{sku} = \sum_{1}^{n} FOR_{sku} \cdot \rho_{sku} \qquad [3]$$

where:
$AFOR_{sku}$: SKU's Forecasts Aggregation in monetary terms.
$\rho_{sku}$: SKU's selling price for each one of the $n$ SKU's.

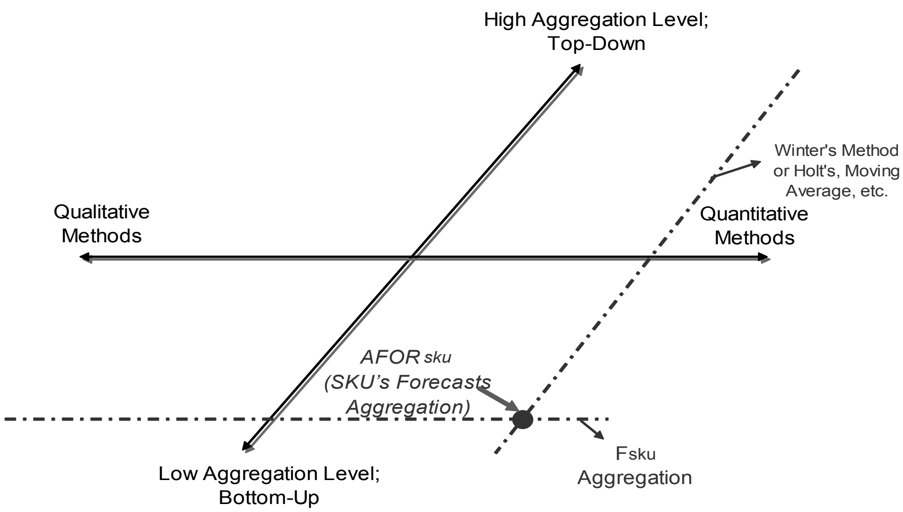


Figure 11. Bottom-Up Calculation and $AFOR_{sku}$. "*Method Category-Aggregation Level* Matrix"

## TOP-DOWN CALCULATION

Once we have set $AFOR_{sku}$, we proceed with the Top-Down Calculation. As stated before, this calculation will consider the use of Qualitative Methods. In our application case, the methods chosen to estimate global forecast were: Opinion Jury, Commercial

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Personnel Proposition and Market Research. This estimation was done in terms of revenue and globally speaking (all SKU's aggregated); note that in our application case, managers and experts had the expert criteria to estimate forecast, globally aggregated and expressed in monetary terms (since they have built their *know-how* during years analyzing global revenues, not product units).

The more decomposed the Qualitative estimations, the more precise the forecast could be; but, a higher amount of macro-families result in a more expensive forecast, since Qualitative Forecasting is an intensive time consuming activity (in man-hours). Qualitative Forecasts go with higher aggregation levels, so this is another constraint to consider, since executives feel comfortable guessing for higher aggregation levels and not in lower levels; this is what we call aggregation level trade-off. It is not an objective of this article to present how to calculate forecast with Qualitative Methods, but to show how to apply them.

Once the global estimation has been made (we will call it Global Forecast or $G_{FOR}$), we will include it in the *Method Category-Aggregation Level* Matrix; please refer to the next figure.

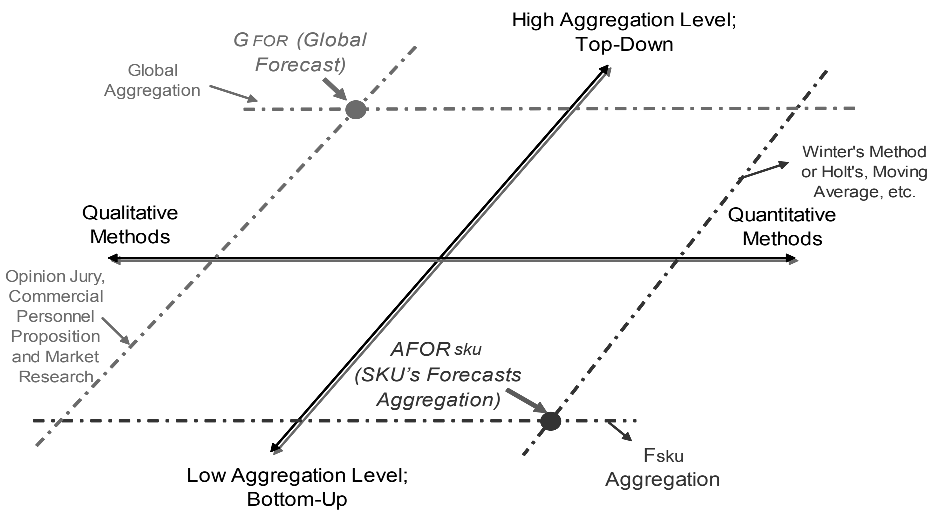


Figure 12. Top-Down Calculation and $G_{FOR}$. "*Method Category-Aggregation Level* Matrix"

### BOTTOM-UP AND TOP DOWN INTEGRATION

Once we have the $AFOR_{sku}$ and $G_{FOR}$ coordinates, we proceed to integrate these two along the "Integration Constant Axis ($\Phi$)". This integrated coordinate will be called Global Integrated Forecast or $G_{IFOR}$. In order to integrate these coordinates we propose the next formula:

$$G_{IFOR} = AFOR_{sku} \cdot (1-\phi) + G_{FOR} \cdot (\phi) \qquad [4]$$

We will present a $G_{IFOR}$ using an $\Phi$=0.95 in the following figure:

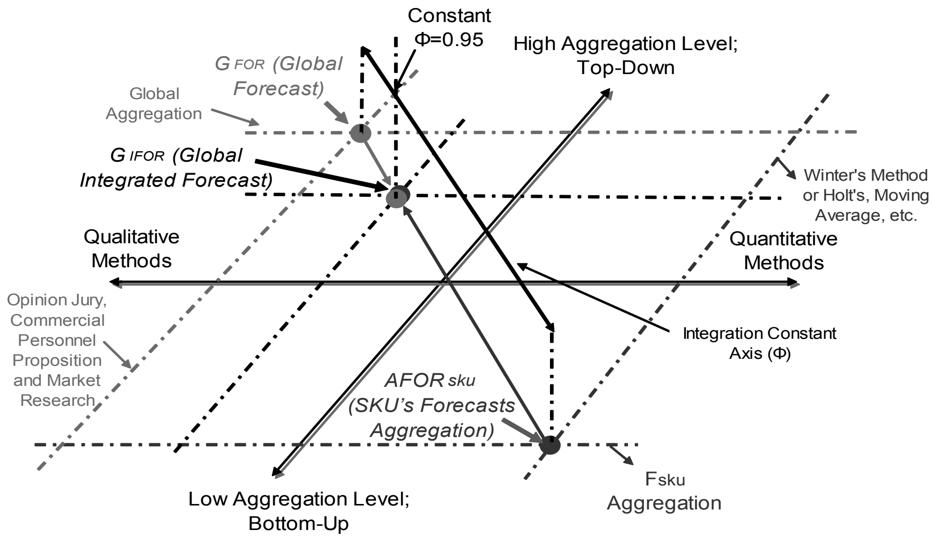


Figure 13. Bottom-Up and Top-Down: $G_{IFOR}$ coordinate. "*Method Category-Aggregation Level* Matrix"

Now, the Global Integrated Forecast ($G_{IFOR}$) must be decomposed in individuals SKU Integrated Forecasts (or $IFOR_{sku}$'s). In order to have this $G_{IFOR}$ decomposed we propose the following formula:

$$IFOR_{sku} = FOR_{sku} \cdot \left( \frac{G_{IFOR}}{AFOR_{sku}} \right) \qquad [5]$$

**ALGORITHM APLICATION**

Once we had the algorithm and its equations, we proceeded to apply it to a Manufacturing Enterprise that produces over 250 different finished products (SKU's). The model was run using the historical data related to 3 years of sales history and proceeded to forecast a six month period (from October 2005 to march 2006).

We started to set the different SKU's families ($F_{sku}$'s) and to "back-cast" its future sales with Quantitative Methods; according to equation (1) and (2) we calculated $FOR_{sku}$ for all of the 250 SKU's. Later on, using (3) and a global level we calculated $AFOR_{sku}$. Using Qualitatives Methods and higher aggregation levels, we defined $G_{FOR}$. Using (4) we calculated $G_{IFOR}$ and then applying (5) we obtained $IFOR_{sku}$.

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When using (4) it is necessary to define the Φ's value. In our case we did set it as Φ=0.95 since expert criteria led us there because of the economical context of the company and its economical expectative; since the economical context has been changing (unstable), managers think that historical data should have little impact in the global prediction and qualitative methods should have more impact; note that even when Φ's value gives $AFOR_{sku}$ light weight, $AFOR_{sku}$ dictates the $IFOR_{sku}$'s sales curve form when using (5).

Among the global results of the algorithm applied to the enterprise we have an average error decrease from 80% for the $AFOR_{sku}$ to 6.2% for the $G_{IFOR}$. On the other hand, it is logical to think that when comparing $G_{IFOR}$ error to $G_{FOR}$ error (the 6.2% error for the $G_{IFOR}$ to 2.9% error for the $G_{FOR}$), $G_{FOR}$ has a smaller error due to its global aggregation level. Nevertheless, note that $G_{IFOR}$ allows us to smooth the possible error related to the qualitative forecasting since it considers sales' history weight; even if error is slightly bigger than $G_{FOR}$, $G_{IFOR}$ allows us to "hear" the historic demand pattern and include it in the forecast's calculation.

In the Manufacturing context, the forecast decomposition plays an important roll since it is critical for the planner to know the forecasted or estimated quantities for each SKU. So, in this sense, decomposing $G_{IFOR}$ into $IFOR_{sku}$ is of great value, since this is useful data for the planner. Even if we loose forecast precision, due to a decrease of our aggregation level, decomposing is a must for the Manufacturing operation.

Regarding the algorithm's results at a decomposed SKU level (this is comparing $IFOR_{sku}$ level vrs $FOR_{sku}$ level), we propose to analyze both forecasts in monetary terms. In order to evaluate the convenience of this algorithm we will contrast the cost of using the $IFOR_{sku}$'s with the cost of using the $FOR_{sku}$'s. In order to contrast these two forecasting methods, we propose to quantify the value of each method in terms of cost. Each method will be compared to the real sales for the forecasted periods; please note that at this moment we know the exact sales quantities for the forecasted period (October 2005-March 2006). To quantify the cost of each forecasting method we propose to consider the over-forecasting cost (overstocking) and the under-forecasting cost (stockout). We propose to consider the overforecasting cost as the monthly carrying cost, and the underforecasting cost as the stockout cost related to the monthly lost sales (in terms of the lost earnings or lost margin related to the products not sold). This procedure helps us to evaluate forecasting methods considering the Manufacturer's real situation (in terms of inventory carrying costs and sales loss).

So, assigning the positive forecast error to MCCR and the negative error to the SoCR we have:

$$FMC = (pe_{sku} \cdot (CCMR) + ne_{sku} \cdot (SoCR)) \cdot \rho_{sku} \qquad [6]$$

where:
*FMC*: Forecasting Method Cost.
$pe_{sku}$: positive error in units for a certain SKU.
*MCCR*: Monthly Carrying Cost Rate.
$ne_{sku}$: negative error in units for a certain SKU.
*SoCR*: Stockout Cost Rate
$\varrho_{sku}$: SKU's selling price.

After comparing both costs, we discovered that the algorithm yields an average cost reduction comparable to a 6.6% of the earnings margin of the product (6.6% out of 18% as the earnings margin), which is quite attractive. Note that the company's MCCR and SoCR values used were around MCCR= 1% and SoCR=18%.

As presented, this algorithm allows the Manufacturer's analyst to calculate the Supply Chain's forecast for all the items that must be fabricated in order to be, later on, Distributed along the Supply Chain in order to be available to final customer. As presented, this case considers a global aggregation for the whole enterprise when applying Qualitative Methods; it is evident that the same algorithm can be applied to Multiproduct Environments but at a lower global aggregation level. In our case, 250 SKU's permitted us to aggregate them in a global prediction. When using this same principle, but in a company with a larger quantity of SKU's, we could decompose the totality of products into strategic ensembles that could be treated as targets to calculate $G_{FOR}$ and $AFOR_{sku}$ and later on get a $G_{IFOR}$; in this sense, we would use the "*Method Category-Aggregation Level* Matrix" concept to each of the strategic ensembles within the enterprise, and later on aggregate its results; we could see it as a "company within a company" treatment.

## BUSINESS STRATEGY AND FORECASTING

Through the Distribution and Manufacturing Process, companies should materialize its Business Strategy, since product availability (in terms of quantity and place) is essential to satisfy Customers. Distribution is seen as the latest step, supplied by the Manufacturing step.

Forecasts can be used as a tool to produce and allocate product to each Customer. According to Carranza (2004), forecasting processes are much more effective when they are performed in collaboration with the entire Distribution Network than when they are individually calculated by each S and C actors; they can be used to strengthen the Supplier and Customer relationships. This collaboration is not natural between members, since it consumes time and energy to do it. Although it is difficult, some businesses have realized about its importance, since improvements in Forecasting and

Planning have had significant success, as stated by Chopra *et al* (2004).

We propose that the implementation of a collaborating forecast is related to the Negotiating Force of the S and C actors. This force difference will also determine Supply Policies. The following are three types of possible relationships based on the different Negotiating Force between Suppliers and Customer when negotiating Supply Policies:

i. Supplier Negotiating Force Superiority over its Customer.
ii. Customer Negotiating Force Superiority over its Supplier.
iii. Supplier and Customer Negotiating Force Parity.

**NEGOTIAGING FORCE SUPERIORITY OVER ITS CUSTOMER**

In this case, the Supplier will set the guidelines according to what is convenient for him, for example:

- Supplier will control *Lead Times* by pushing his customers to place purchase orders with as much possible time in advance. Doing so, Supplier will increase the precision of his forecast (since he will produce "make-to-order"). This practice will help him reduce his operative costs.
- M.O.Q's policies (Minimum Order Quantity) will be implemented so that the Supplier could profit from the production and transportation economies of scale. Suppliers sometimes pay for the transportation cost as a *Customer Service Policy*, but their main objective is to force the customer to place M.O.Q's Purchase Orders. All these policies should be tacitly accepted by the market and customers; otherwise they become counterproductive as a risk of potential market loss.
- Supplier will try to push to its Customer the Economical Inventory Risk related to Forecasted Sales; S will try to push the product to C at the earlier possible moment.
- Supplier will not be worried to develop and to train its Customers with Forecasting Tools and Supply Policies in order to optimize the Chain. The interest is unilateral and S makes decision aiming his local optimal point. Sometimes, this policy could yield short term profits but later on long term losses (so is the case when the Supply Chain gets saturated due to supplier and customer communication problem; the *Beer Game* is a parody related to this problem as evoked by Carranza (2004). These communication problems could be very expensive for Suppliers since its Production Capacity has to be changed accordingly.
- Supplier S will offer a slightly better Customer Service Level in terms of his competitor's Service Level. The Strategy would be to differentiate from competitors but not completely exceed them. This is how S will avoid his Customers to place purchase orders to the competition. For example, a Customer will prefer a Supplier that offers him the possibility to demand partial and

immediate shipments, with shorter lead times and the same quality (this is an example of a differentiating strategy). Please see Figure #14.

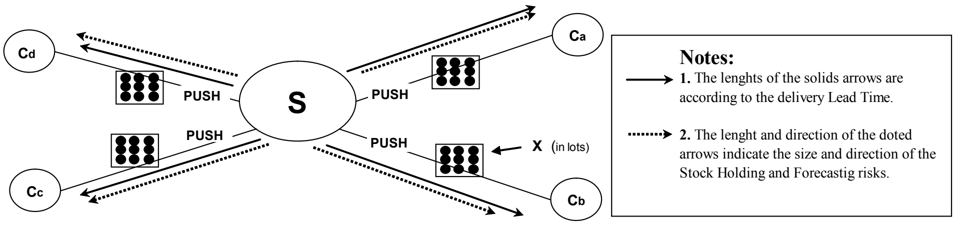


Figure 14. Basic Supply and Distribution Network: Supplier Negotiating Force Superiority over its Customer

**CUSTOMER NEGOCIATING FORCE SUPERIORITY OVER ITS SUPPLIER**

In this case, the Customer will set the guidelines according to what is convenient for him. For example:

- Customer will prefer his Suppliers to follow *Just in Time* supply policies. Since its commercial advantage allows him to exploit the equation service, the customer will aim to have the product at the Right Time, in the Right Place, and in the Right Quantity (an example could be the supermarket sector and its relationship with its suppliers). Since Suppliers should react immediately, this makes them deal with all the Forecasting and Planning burden. This practice pushes the risks towards Suppliers. *Just in Time* orders are characterized by its small sizes and high frequencies due to short lead times.
- Customer will foster his Supplier proximity in order to guarantee its product supply and flexibility even under strong demand changes. In some cases, C will foster S physic proximity in order to minimize the transportation time (classic example of the automobile industry).
- The economical inventory holding risk will be pushed toward S. It is a frequent practice for the biggest C's, to make its Suppliers to carry a fixed physical Safety Inventory in order to guarantee an agreed Service Level (this is usually done under economic penalty conditions for not fulfillment cases). This penalty pressure makes the Supplier to have a bigger need for Forecast accuracy or higher Safety Inventory levels.
- Another Suppliers strategy is to guarantee a Customer Portfolio that allows S to supply many other customers with reasonable size (as the $C_d$, $C_c$ and $C_b$ case in figure #15). This allows S to equilibrate the higher economic pressure that the biggest C puts on him (see below figure).

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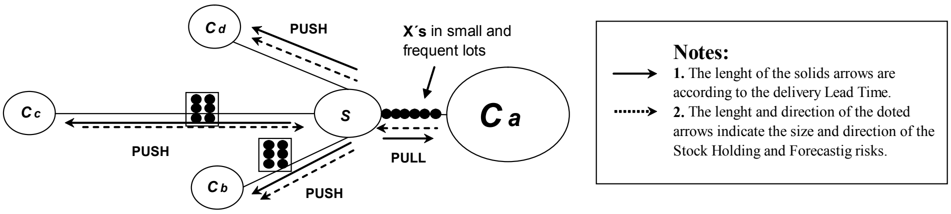


Figure 15. Basic Supply and Distribution Network: Customer Negotiating Force Superiority over its Supplier

## SUPPLIER AND CUSTOMER NEGOTIATING FORCE PARITY

In the case of Negotiating Force Parity, both actors will try to set the guidelines according to what is convenient for them, for example:

- Both actors will be interested in mutual growth.
- Mutual coordination will be aimed in order to set the Supply Policies that works the best.

The Negotiating Force Parity condition could come from many possible sources, for example:

i. **Negotiating Force Evolution through time for one of the actors.** For example: aggressive Customer requirements (costs reductions, shipping conditions, etc.) sometimes make small and medium suppliers go bankrupt, or to "merge" with a stronger actor (or even to sell the company). Later on, the market that these competitors used to own, is absorbed by the strongest "survivor" Supplier who now gains Negotiating Force toward Customers.

ii. **Negotiating Force gains due to a Strategic Advantage.** For example: a big Customer wants to develop a strategic Supplier in order to guarantee his requirements supply such as: quality level, physical proximity, supply flexibility, technological advantage, etc. In this case the Supplier gains Negotiating Force.

## FORECASTING AS A COUNTERBALANCE FOR NEGOTIATION FORCE DIFERENCES

These three scenarios highlight the pressure that each actor has. We can compare this pressure to the *Implied Demand Uncertainty* concept since, according to Chopra *et al*. (2004), it "is the resulting uncertainty for only the portion of the demand that the supply chain must handle and the attributes the customer desires". This pressure based on the Implied Demand Uncertainty could also come from the differences in *Negotiating Forces*.

Nowadays we can hear from collaborative planning techniques such as CPFR (Collaborative Planning, Forecasting, and Replenishment); these techniques have been successfully implemented in *Negotiating Force Parity* situations, since both actors are truly interested in mutual benefits, which motivate them to allocate their resources to this project. Chopra *et al.* (2004) shows some of this examples.

In many cases, *Force Superiority* can not be exploited by stronger actors in a sustainable way without considering the long term impact over the weaker actor (especially if the weaker actor can find an advantage in order to be considered by the stronger as a critical strategically speaking actor). The weaker actors could profit from this fact and use it as an argument in order to negotiate and foster teamwork to improve the Supply and Distribution Network.

Our model proposes the importance of using simpler collaborative techniques in the *Negotiating Force Non- Parity* environments; in this sense, the weaker actor requires to improve its products supply management through a forecasting process improvement, as is the case of the Method we are proposing, and therefore reduce its pressure or *Implied Demand Uncertainty*. This improvement can help the weaker actor to counterbalance its Negotiating Force by being proactive with the stronger actor and fostering a collaborative environment to improve the service the weaker offers. We propose that this initiative must come from the weaker actor; a possible tool for weaker actors to reach this is through the use collaborative Forecasting Process.

Within the reality of the Supply Chain, since companies usually have different suppliers and customers, companies play different *Negotiating Force* rolls; in this sense, companies could play the weaker or stronger actor roll depending on each case. When Planning the Multiproduct Supply Chain, it is evident that each company has to concentrate in the most important of these relationships; a Paretto analysis is recommended in this situation.

## CONCLUSION

Distribution and Manufacturing Strategic Planning is critical for companies that deal with Manufacturing and Distribution processes. Both processes have to be planned in accordance one with another.

Forecasting processes can be implemented in the Distribution network in order to guarantee product availability by improving the product allocation process within the Supply Chain (within each Supply Chain's node). Forecasting processes can be implemented in the Manufacturing process in order to improve the availability of product to supply the custumer's needs in terms of quantity and place.

When planning the Manufacturing and Distribution processes it is critical to consider the company's position within the proposed *Negotiating Force* frame; the company must understand its position and try to improve it strategically. Customer's or Supplier's pressure can be handled and reduced through forecast as a step to reach collaborative forecast. Since in the Multiproduct context there are multiples customer-to-supplier and supplier-to-customer relationships, each company has to understand which of these relationships represents the critical ones in order to strategically improve them.

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# Shifting from conveyor lines to work cell-based systems: the case of a consumer electric products manufacturer in Brazil

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**Abstract:** The division of process in short-cycle tasks performed along belt conveyors became a widely sought organizational pattern in manufacturing operations following the emergence of mass production. Later on, when manufacturers had to face the challenge to fulfill more diversified demands, the derivation of "mixed-model assembly lines" extended the potential utilization of belt conveyors. However, more recently, a number of organizations are abandoning their utilization and switching to the adoption of work-cell based assembly systems. This article investigates such shift in operations strategy from an international perspective. Firstly, it discusses the experience of electric and electronics industries in Japan, where this trend became a major trend in the late 1990s. To support the understanding of its underpinning rationality, a conceptual review on the advantages and disadvantages of belt conveyor assembly lines is included. Next, it presents an in-depth longitudinal case study of a consumer electric products manufacturer in Brazil that embarked on a program to migrate from the utilization of conveyor lines to the work-cell based assembly system in one of its plants. The implementation of a pilot work-cell in a kick-off project is analyzed and

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the prospects of the ongoing efforts to deploy similar maneuver in other facilities is presented.

**Keywords:** belt conveyor, assembly line, work-cell, line balancing

## INTRODUCTION

The conveyor line production system is one of the most representative epitomes of the Fordist mass production paradigm. The classical approach of optimizing production line design and operation by dividing a whole process in short cycle tasks, applying line balancing, and laying out the required resources sequentially along belt conveyor lines, by means of which parts and products are automatically transported, for long has been justified due to advantages such as;

- economies of scale achieved in volume production,
- ease of production control,
- shorter throughput times, and
- possibility to employ low-skilled workers.

Although the exploitation of conveyor line system has leveraged industrial growth, it exhibits weaknesses and deficiencies which bring problems to its adherents. However, historically, decision makers in manufacturing firms have relieved these drawbacks considering its compensating advantages.

The significant transformations that have reshaped market, technology, labor and enterprise organization patterns since the emergence of the Fordist paradigm in the early 20$^{th}$ century motivated the development of alternative systems more suitable to the new business and competition circumstances. The evolutionary emergence of mixed-model production lines, transfer-lines, and flexible assembly lines (Hill, 1993), contributed to expand the range of cost efficient applications of conveyor line system and thus prevented the obsolescence of this approach.

However, leading manufacturers are now revisiting the traditional standpoint of leaving out the inherent disadvantages of the conveyor line system. In this context, it is worthy noting the striking trend of abandoning conveyor lines currently observed in some industries in Japan (Isa & Tsuru, 2002; Miyake, 2006).

The purpose of this article is twofold. Firstly, it aims to bring to light the trend of replacing the utilization of belt conveyor lines by an alternative production system based on work-cells that emerged in some manufacturing industries in that country and discuss its grounds and motivations. The other objective is to present an in-depth study of a manufacturing plant in Brazil where the organization of the production process is undergoing an outstanding revamping movement in which an approach similar to the one taken by the above mentioned Japanese manufacturers is being deployed. From the theoretical point of view, this empirical study is motivated by the issue of testing greater generalizability of this shift in production organization mode, for attaining improved operational performance, in a quite different setting like the Brazilian industry.

In the next sections, the backgrounds of this trend are outlined and the shortcomings and disadvantages of the belt conveyor-based assembly systems which motivated the emergence of an alternative production system in Japan are discussed. Next, an in-depth longitudinal case study of a manufacturing plant in Brazil that has embarked on a similar change process is presented. Finally, the main aspects related to the experience undertaken at this unit of analysis, its prospects, and the conclusions of the case research are discussed.

## THE EMERGENCE OF THE CELL PRODUCTION SYSTEM IN JAPAN

As consumption patterns become increasingly sophisticated and manufacturers strive to improve their competitiveness offering quality products at competitive costs, broadening product mix, and keeping it attractive by launching systematically new products, markets have become more turbulent. The volatility of market demands has impelled leading manufacturers to search the development of alternative production systems that might enable them operate more responsively (Katayama & Bennett, 1996).

The initiatives towards reorganization of production system in progress in Japan, especially, in the electric and electronics industries, provide evidences of this movement. In these industries, high/medium volume products usually have been produced in mixed-model production lines (Hill, 1991) equipped with Advanced Manufacturing Technologies (AMTs) that relieve reliance on labor.

However, following the burst of the so-called “bubble” economy in Japan by 1991, it was observed a reversal in the trend toward large-scale automation (Tsuru, 2001; Isa & Tsuru, 2002). This was motivated not only by the economic stagnation which seriously curbed capital investments, but also because a significant part of investments in automation resources became controversial for falling short in providing bold contributions to productivity improvement.

In this context, industry observers ascertained that by mid-1990s an alternative approach to design and organize production system was arising in some industries in Japan relying on more human-centered systems resembling the “craft work” of traditional workshops (Williams, 1994; Shinohara, 1995).

Isa & Tsuru (2002) studied this strategic turnaround in which the approach of dividing work into short cycle tasks performed along belt conveyor has been replaced by workplace innovations that enable the accomplishment of both high labor efficiency and enhanced flexibility. This organization change includes measures like the (a) assignment of more challenging and meaningful functions to workforce by multi-tasking, purposeful learning and skills development, involvement in continuous process improvement, and greater autonomy; (b) implementation of workstations designed to foster high performance work, and (c) reliance on low-cost automation (LCA) resources. The pattern of production system that emerged from this turnaround has been called "cell production system".

It is worthy distinguishing it from the preceding and more well-known concept of cellular manufacturing system (also known as cellular layout or group layout) as both can be easily confounded (Miyake, 2006). The latter is a plant organization approach which advocates the laying out of production resources in such a way to form manufacturing cells self-contained with all necessary machines and tools to produce a given set of similar products (Hill, 1991; Luggen, 1991; IJMTM, 2001). This contrasts from the traditional process (or functional) layout paradigm which considers the arrangement of process areas by grouping resources with similar capabilities. For Luggen, the cellular organization essentially aims the tradeoff of inter-departments material handling for intra-department material handling.

Cellular manufacturing system and cell production system represent two resembling but distinct production system design concepts. While the former is primarily driven by the objective of reducing materials flow complexity in typically capital-intensive systems to produce a more stable variety of items, the latter is an approach to boost plant responsiveness and cost efficiency to cope with more volatile demands relying on more labor-intensive systems. However, both of them share the idea of organizing resources in production cells driven by the rationale of creating smaller "plants-within-a-plant" which yield shorter throughput times and lower work-in-process (WIP) levels (Miyake, 2006).

## THE LIMITS OF THE CONVEYOR LINE PRODUCTION SYSTEM

In a seminal field study on the trend of shifting from conveyor line system to cell production system, Shinohara (1995) investigated initiatives taken in the electronics industry by firms like NEC-Nagano, Yamagata Casio, Olympus, Pioneer and Santronics. More recently, Asao et al. (2004) investigated similar conversion cases in plants dedicated to assembly of printers, digital cameras, digital video cameras, and module parts for digital electric equipment. These authors investigated how managers of the investigated plants perceived the use of conveyor lines nowadays and reported a growing concern with their intrinsic weaknesses, which has impelled the awareness that the advantages of this production system may not pay off its adoption any more.

Quoting the perspective of a Japanese management institute, Shinohara (1995) remarked that conveyor lines present a series of detrimental aspects for productivity which may be represented by the following seven waste categories:

1. under-utilization of workforce due to the fact that line cycle time is bounded by the slowest worker
2. waste of time in reaching work-piece on conveyor and returning it onto conveyor after task completion
3. waste of inventory due to the holding of work-in-process (WIP) between successive stations
4. waste due to defective parts and rework
5. waste of resource capacity during product model changeover
6. waste due to difficulty in promoting mutual support among workers
7. waste of waiting time by workers operating partially automated short cycle process that does not allow handling of multiple machines.

Besides these, Asao et al. (2004) pointed out additional categories of losses as follow: i. line balancing loss, ii. double checks, and iii. extra space. These authors complemented that production in conveyor lines reveals other types of problems such as;

- reliance on large investments in facilities,
- reliance on indirect and support personnel who generate no added value,
- underutilization of the workers' intellectual capacity, and
- the evident rigidity of this production system that makes product model changes, introduction of new products, and process changeovers costly and time-consuming, and moreover, layout reconfiguration extremely difficult.

Also, the very nature of the process division and organization along belt conveyors brings other disadvantages as:

- the line only runs in case all stations are available and ready to operate, and
- it entails the adoption of prevalently one-sided physical motions.

Considering the conveyor line system from a broader perspective, Asano (1997) remarks that larger lines are especially more fragile in coping with production volume decline. Given the demands to justify the huge investments they required, the implantation of conveyor lines leads to the concern of accomplishing the highest capacity utilization rates at the expense of large and costly inventories of work-in-process and finished goods.

In earlier times, the disadvantages of the conveyor line system used to be overlooked since it provided a reasonable operational solution in view of the competition patterns that prevailed. However, manufacturing managers in Japan have revealed an increasing discomfort with these weaknesses which evince the limitation of the conveyor line system in enabling the organization respond to the dramatic changes that are reconfiguring the business and market environment.

Moreover, since the late 1980s, Japanese manufacturing firms have demonstrated great concern with the declining attractiveness of the work in conventional assembly lines and rising turnover in this type of job positions. Even in plants of Toyota Motor, where the celebrated lean production system was conceived, this issue has called for keen attention of management, motivating the review and improvement of work conditions in final assembly lines (Fujimoto, 1999).

The criticism against the conveyor line system thus can be summarized in the following fundamental limitations:

- The losses that are inherent to processes performed along conveyor lines, though not formally measured by managers, are in fact of much greater magnitude than usually supposed, and increase with the line length.
- Conveyor lines can provide the most efficient process solution when dedicated to a specific product or product family. On the other hand, this implicates in a structural rigidity that makes terribly cumbersome to cope with product model changes, product mix variation, and lot size reduction.
- The highly repetitive minute tasks and difficulty to promote group interactions that distinguish manned conveyor lines impose a monotonous and alienating work environment to the workforce.

## RESEARCH METHOD

The development of this work was based on case study method. According to Yin (1994, p.13), a case study is “an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident”. Among the different case study design alternatives, the single-case study design was adopted. A single case study is appropriate where it represents a critical case or meets all criteria for testing a theory, or where it is a revelatory case (Yin, 1994). A single case allows the investigation of the phenomenon in depth to provide rich description and understanding.

The focused case involves the experience of a major consumer electric products manufacturer established in Brazil whose name is omitted in respect of the confidentiality requested by the firm, and thus is refereed to as CEPM-Br. This firm decided in 2005 to tackle a project for exploring the concept of replacing the organization of assembly process around belt conveyors by a system based on work-cells. Given the pioneering nature of such organization innovation initiative it can be considered a revelatory experience, being one of the earliest examinations of the phenomenon involved outside the context of the manufacturing industries in Japan and Japanese manufacturing corporations for academic purposes. For this reason, besides providing a description of an actual experiment and mapping its key variables, this case study intends to contribute in the inductive construction of the theories behind the observed experience.

Two authors of this article were actually engaged in the aimed change process as participants of the CEPM-Br team that conducted this project. This not only facilitated direct observations and access to primary sources of data but made possible a close follow up of this real-world situation for grasping an in-depth view of its evolution and building a reliable understanding of its issues and underlying rationale. This study was developed over a period of approximately one year, from June 2005 to May 2006 in two stages. In the first stage, one of the authors – a student of a major undergraduate production engineering course – participated in the project since the very beginning as part of a internship program undertaken in the plant taken as unit of analysis. This made possible the grasping of the initial situation, the accompanying of the change process evolution, and thereby the realization of a detailed description of the case. In the second stage, when the change process had already advanced substantially, the other author – a senior manager in the focused plant – who had a critical role as a major change agent contributed in the ex-post assessment of the case and its outcomes.

The analysis of the case was also supported by other three informants; a corporate senior manager who supported this change process, and by two staff members employed at the unit of analysis who participated in the change process as *kaizen* support analysts and, therefore, had an in-depth understanding of operational aspects of the case. These contacts were realized in earlier stages of the change process and later on when it was firmly on course.

Additional information could be directly gathered from memoranda of three on-site visits made by the main researcher of this work and other primary sources like internal reports and presentations, documentary video, and spreadsheet data. These data gathering means provided multiple sources of information and views to enrich the description of the case and ensure the consistency of its analysis.

## THE CASE OF A CONSUMER ELECTRIC PRODUCTS MANUFACTURER IN BRAZIL (CEPM-BR)

### Backgrounds of the CEPM-Br case

CEPM-Br was a firm of national capital, which was incorporated by a leading global manufacturer of consumer electric products in the 1990s. Despite this overtaking CEPM-Br's products are still traded with its original brands in domestic markets and local management has been given great autonomy to deploy the operations strategy. Nowadays, it produces a large variety of electric products for home in four manufacturing sites.

Yet in the mid-1990s, other global competitors have aggressively entered in the Brazilian market of consumer electric products seizing significant market shares.

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This has awakened the concerns of CEPM-Br's management to strengthen the overall competitiveness of its operations. The case here presented is about the turnaround undertaken in one of its plants aiming the reconfiguration of the production system so as to increase its performance in terms of productivity, quality, flexibility and responsiveness. This plant is located in a site with 50,000 $m^2$ of built area, employing about 1,500 people and is dedicated to the production of a specific type of product.

The operations of this plant are based on a hybrid production system combining push and pull techniques. While the production program in the final assembly process is defined in make-to-stock (MTS) mode, the supply of the required parts are either pushed by previous stages or pulled from supermarkets where internally stamped and coated parts are stocked.

When this turnaround was initiated, the final assembly process was organized around 3 long assembly lines equipped with belt conveyor ranging from 25 to 35 meters. Each line had capacity to assemble several product models. When completed, the assembled products are quite heavy (31-55 kg) and large with its external dimensions ranging from 495 to 920 mm. As these products are quite sizeable, belt conveyors were utilized to support the product body during the execution of manual assemblies and to move it along the main assembly process.

The capacity of each line had been established to vary from 50 to 150 units per hour depending on the product complexity. An implication of this was that the production cycle time varied from 24 to 72 seconds imposing short cycle tasks to a workforce that ranged from 75 to 85 operators. Approximately 62% of them were assigned to main assembly and the remaining to connected sub-lines which fed subassemblies. Because of the large number of workstations comprised by the lines, product changeover was time consuming and this motivated production planners to produce large batches. A total of 130 product models were assembled and finished goods inventories were very high.

Driven by the need to increase productivity, the management of the plant undertook efforts to streamline processes based on the lean production approach. A series of process improvement actions were then carried out by systematically identifying losses, and applying lean concepts and techniques. Thus the design of methods, workstation layout, workbench, and auxiliary devices were reviewed, and work load was rebalanced, bringing significant gains as follow: i) Line efficiency could be raised significantly and this enabled the shutdown of one of the four belt conveyors operated in the unit of analysis in early 2005; ii) the remaining three belt conveyors were shortened about 35% in length, iii) workforce reduced nearly 9%, and iv) occupied floor space reduced 55%.

These gains could be effectively sustained, however as the performance of the rationalized assembly lines gradually rose, opportunities for further significant improvements became unlikely. Furthermore, despite the gains, the improved assembly lines still featured some evident deficiencies as follow:

- short cycle times
- short distance between successive operators
- poor line balancing efficiency

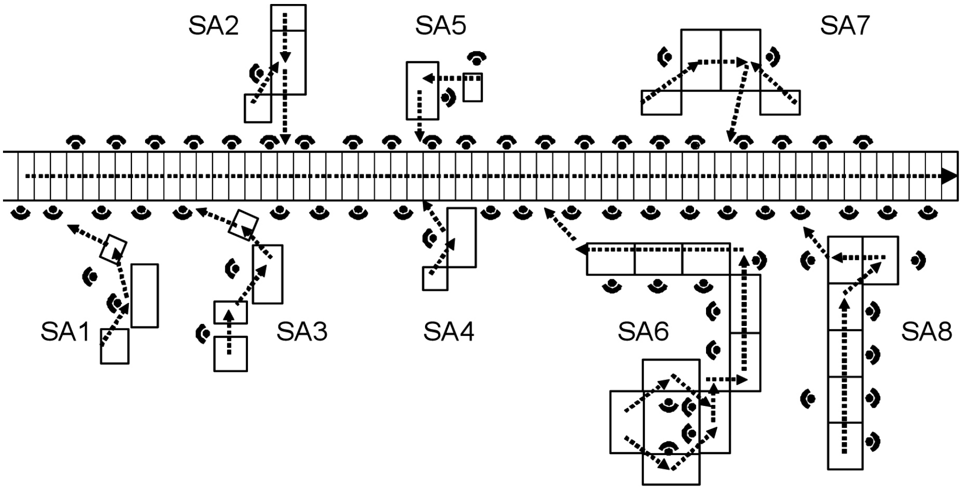


Figure 1 - Layout of the belt conveyor assembly line.

Figure 1 exhibits the layout of one of the lines in which 42 operators were employed in the main assembly process and 26 operators were employed in subassembly (SA) processes. Figure 2 indicates that in a certain line, for a cycle time of 22 seconds, the line balancing losses were of 29% and 22%, respectively, in the main assembly and subassembly.

The management then realized that to overcome these deficiencies, a production system innovation should be seriously considered given the limitations to obtain further significant improvements maintaining the utilization of the conveyor line system.

This motivated managers to consider the challenging proposal of abandoning traditional paradigms, by replacing large conveyor lines by more compact and agile assembly systems organized in work-cells.

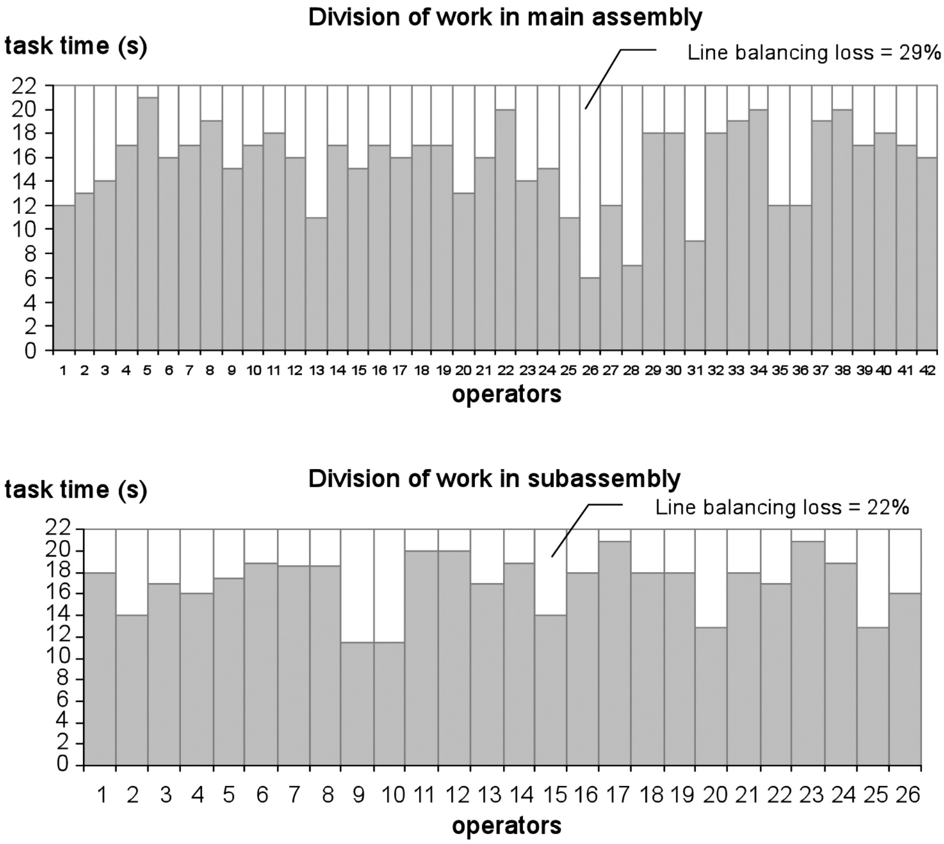


Figure 2 - Division of work in conveyor line process.

**The production system change project in the final assembly process**

To test the feasibility of this shift, a pilot work-cell was initially designed for the final assembly of a product model whose demand was relatively low as the risks should be minimized and few people could be transferred from the operating lines to experiment the alternative process of production. The implementation of the pilot work-cell involved a team coordinated by the production manager, assembly line coordinators, production engineering experts, and *kaizen* support staff.

The design of this work-cell started by disassembling step by step a unit of the product that would be assembled. Each separated part, was laid out on the floor in the reverse sequence of the assembly process and the set of all individual parts were arranged in such a way to define a U-shaped line.

The design of the pilot work-cell followed some guidelines. Firstly, it was defined that the product would not be moved by conveyors. Thus, a low cart was built in-house so that the product could be laid on it and completed as it is conveyed smoothly through successive workstations positioned along a U-line where a subset of parts would be assembled.

Next, with regard to work organization, it was defined that in the main assembly, operators would be assigned to perform complete processes. As an implication of this, instead of being placed in a specific workstation, these operators would rotate cyclically the U-shaped cell in a row following the subsequent operator in the so-called "rabbit chase" mode, completing one product per cycle (Suzaki, 1987). The adoption of U-shaped cell layout was fitting for minimizing the distance between the position where the cart carrying a finished product ahould be left at the main assembly exit, and the entry point from where the operator should start the next assembly cycle.

Also, to minimize the length of the main assembly route in the U-shaped cell, the preparations of subassemblies were positioned outside to take place in connected workstations. These guidelines contributed to make the work-cell more compact.

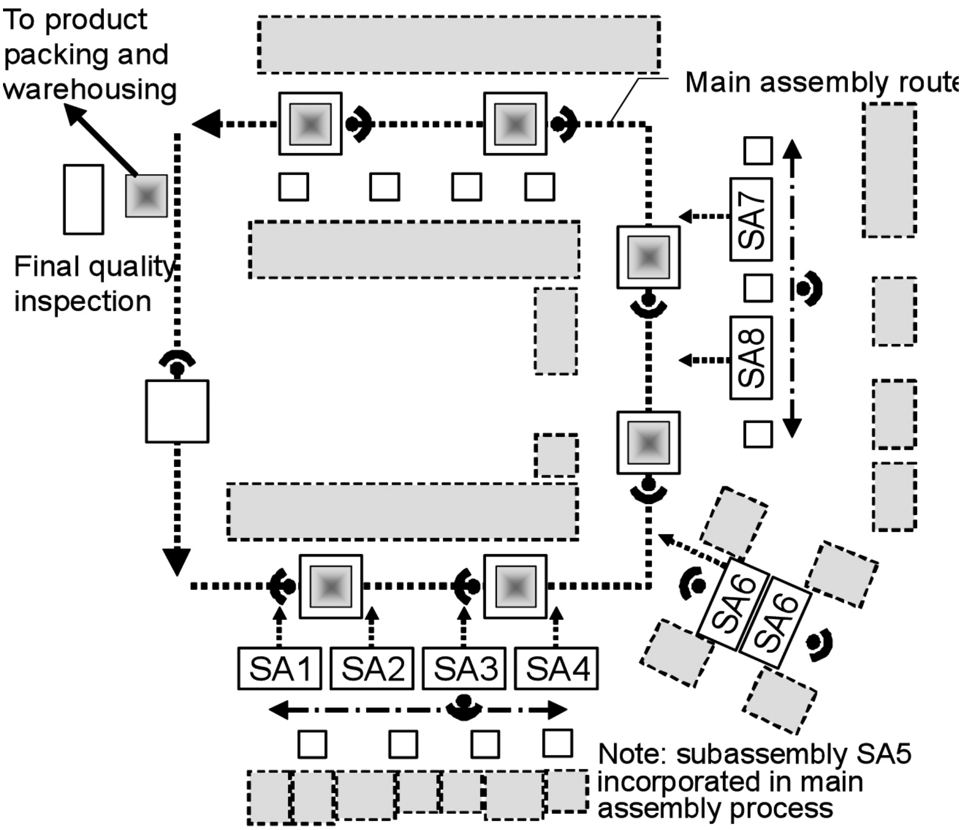


Figure 3 - Layout of the pilot work-cell.

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Experienced operators were then observed performing the assembly tasks in the work-cell and motion times were measured by the *kaizen* staff. Considering this separation and applying a cell balancing method, the total 80 motion elements required were initially grouped to be performed by a team of just 11 operators in a cycle time of 144 seconds; 7 in main assembly and 4 to subassemblies as shown in Figure 3. As indicated in Figure 4, this allocation reduced line balancing losses in the main assembly and subassembly processes to 5% and 9%, respectively.

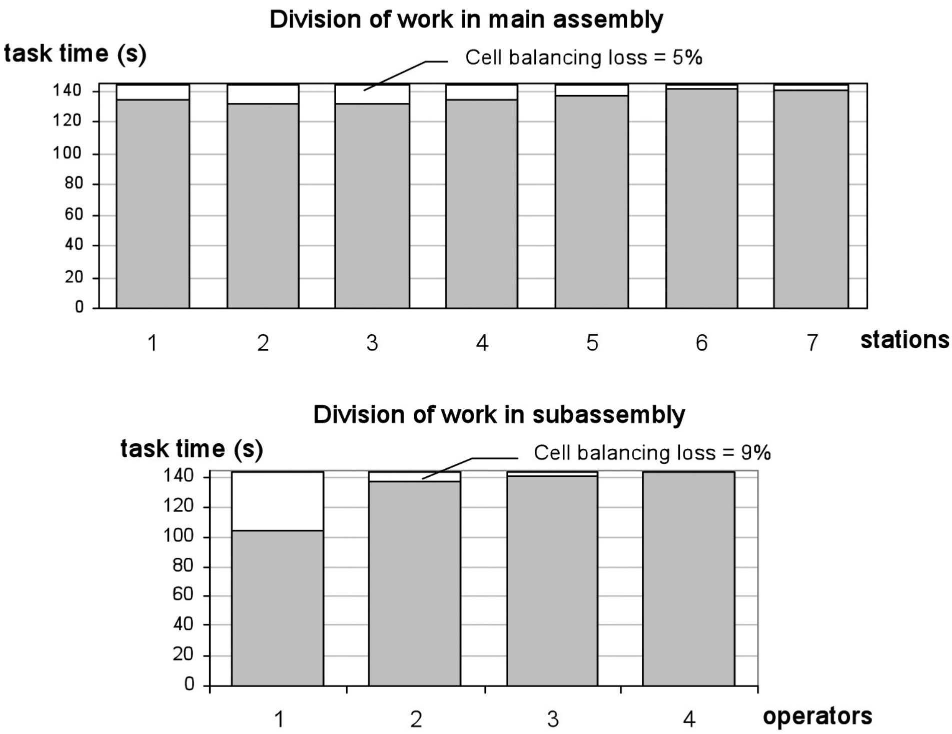


Figure 4 - Division of work in the pilot work-cell.

A pilot work-cell based on this configuration was built and in August 2005 its trial run started with a few operators since the belt conveyor line that would be replaced was still running hindering the removal of more workers. This testing stage was critical for the following issues:

- Job enlargement: Operators used to perform fragmented tasks within short cycle times in conveyor lines should be trained to undertake a broad scope process in the main assembly process that required 955 seconds.
- Parts replenishment logistics: An area called "refrigerator", where parts pulled from "supermarkets" in original large racks could be stored, was installed outside

the work-cell, otherwise more space would be needed in the cell. To make each workstation as compact as possible and at the same time increase the amount of parts to be assembled by each operation, small bins were arranged to facilitate parts feeding at points of use. Typically, the stocks kept at points of use are sized to fulfill between 30 and 60 minute of production needs. An operator called *mizusumashi* (Miyake, 2006) was assigned to cyclically transfer parts in small quantities from the "refrigerator" to these bins as illustrated in Figure 5.

- Process improvement: Initially, the man-hour productivity was lower in the pilot work-cell. To make it comparable to the productivity in conveyor line system, the *kaizen* staff worked intensively close to operators to rationalize the work in each workstation (in main assembly and subassembly), by developing fixtures that facilitate task execution and quality assurance, improving ergonomics, identifying equipment requirements (e.g. electric screwdrivers, riveting tools), and revising process sequence. The participation of the operators was critical to analyze the process and implement these improvements effectively.

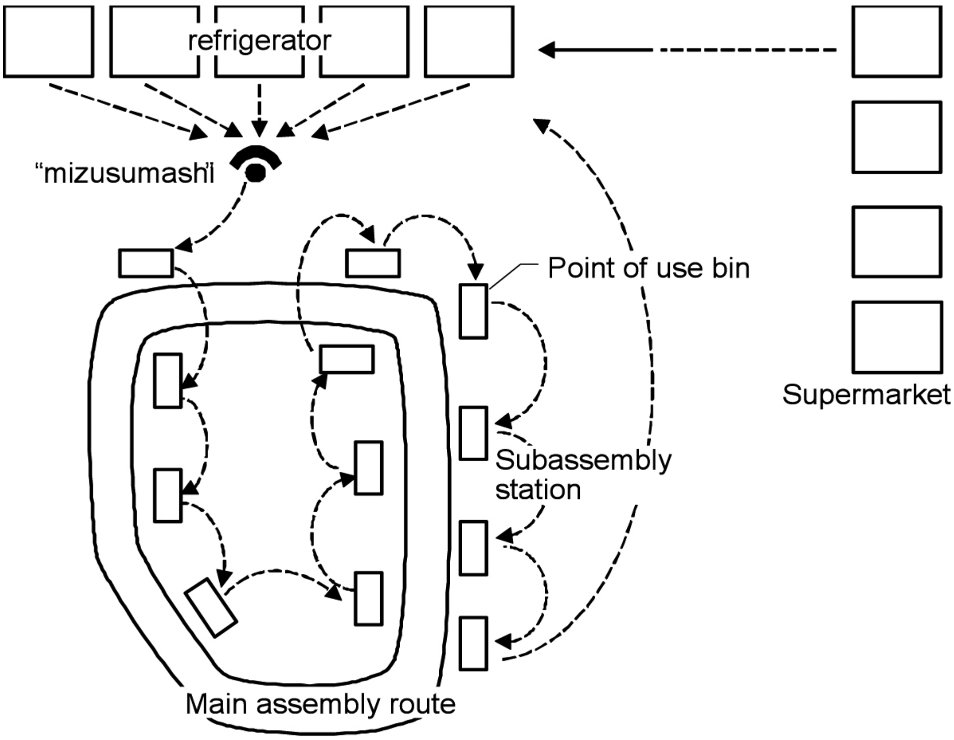


Figure 5 - Replenishment of point of use bins.

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When the pilot work-cell was properly configured it was transferred to a definitive location by September 2005. This could be carried out swiftly in about 6 hours, so that in the following day it was already operational. The low investments required by the pilot work-cell besides the ease and rapidness of building, adjusting, transferring and reinstalling it in comparison to the cumbersome efforts that conveyor line systems would require were quite impressive from the managerial viewpoint.

The work team was then complemented in the pilot cell and they achieved promising performance levels in terms of productivity and quality. These results convinced the managers to roll out the strategic project of changing the production system in assembly process. A plan was then devised to replace the 3 conveyor lines by a set of 8 work-cells in the assembly process as shown in Figure 6.

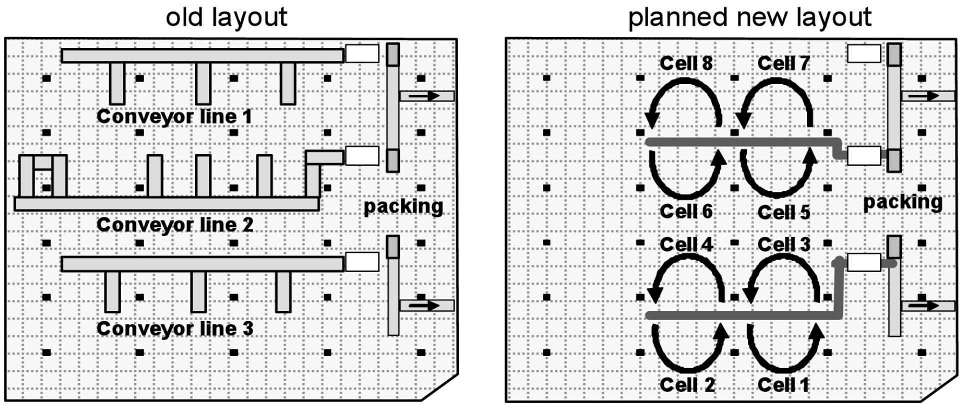


Figure 6 - Old and new layout for the assembly process.

The decision of this change process was also corroborated by encouraging impacts on workforce. Monitoring the operators' willingness to work in a context of enlarged jobs, it was observed that capable operators could not only undertake a much broader scope process in final assembly but also contribute to reduce nonconformities since this implied testing their own work. Moreover, the U-shaped layout promoted constant sharing of knowledge and practical experience among the team members facilitating the development of group competences. Soon each operator grasped a systemic view of the entire process and incorporated a keen sense of responsibility.

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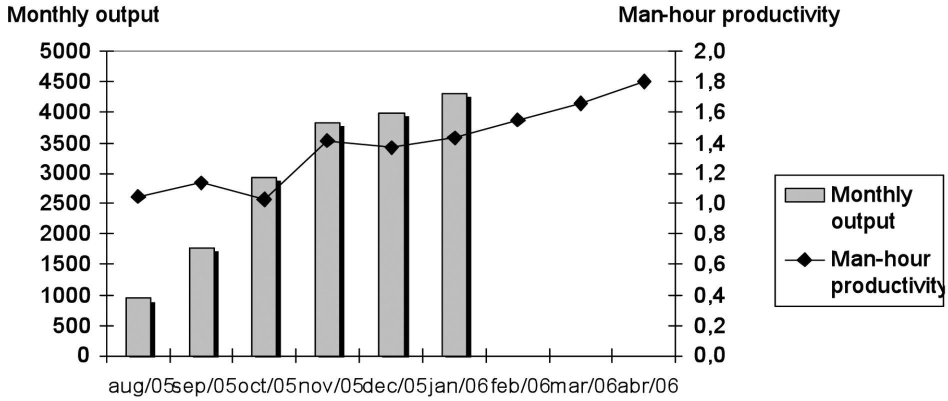


Figure 7 - Man-hour productivity in pilot work-cell.

## Operational performance of the work-cell system

As additional operators were included in the work team the output of the pilot work-cell increased. Figure 7 indicates that during the production ramp-up, man-hour productivity has clearly raised as the learning process and *kaizen* activities advanced. It is worthy mentioning that in this period the number of product models assembled was also increased.

The migration to the planned new layout advanced as additional assembly work-cells were built. Figure 8 indicates the chronology of each cell building and implementation process. By the end of 2005, a total of 4 work-cells had been implemented. The other 4 work-cells were implemented in the first quarter of 2006. The change process advanced gradually and in its course, the involved change agents developed and refined a proper planning and implementation method for the type of assembly work-cells they conceived. The intense learning attained by tackling the problems and challenges faced during the installation, try out and production ramp up of the initial cells enabled the organization to improve and shorten the preparation of the following work-cells.

Figure 8 also indicates when each belt conveyor lines were eventually shut down. The three conveyor lines were dismantled and removed from the plant in stages and thereby the new work-cells were gradually installed in the released spaces.

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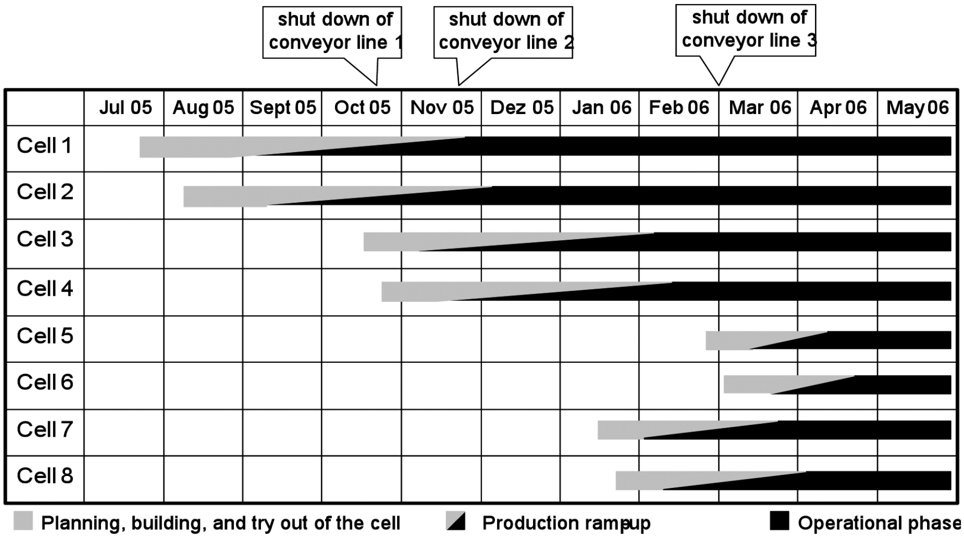


Figure 8 – Chronology of the cells implementation process.

With regard to production ramp-up time of assembly work-cells, it was noticed that the organization could manage to reduce it significantly from about 3 months taken in the earlier work-cells to just one month in the latter ones. This was greatly supported by the organizational expertise developed for work-cell design; assembly method planning and improvement; and on-the-job training of operators.

Based on data gathered in the subject migration project, Table 1 compares some attributes and performance indicators of the production in a conveyor line and in a work-cell, indicating the advantages of the latter one in supporting the shortening of production lead time, reducing resources requirements, and fostering manufacturing agility.

Quality assurance, has also benefited from this change as in the new work-cells a single operator handles the main assembly process of a product. This enhanced traceability of root causes of nonconformities, promoted self-testing and self-control, and stimulated cooperation among team members.

Table 1 - Comparative data.

| | Conveyor line | Work-cell |
|---|---|---|
| Man-hour productivity [a, b] | 100 | 129 |
| Setup time (minutes) [b] | 9 | 5 |
| Throughput time (minutes) [b] | 30 | 15 |
| Job span (# of workers in main assembly) | 42 | 1 |
| Work in process (# of products) | 33 | 11 |
| Defective rate [a] | 100 | 30 |
| Required floor-space [a, c] | 100 | 75 |
| Relocation time [d] | at least 2 months | 1 day |
| Investment [a] | 100 | 17 |

Notes: [a] Index number relative to line
[b] average figures
[c] includes area to store parts and components at points of use
[d] time span until starting production try out after transfer and reinstallation

The greater flexibility brought by the new production system was complemented by comprehensive improvement actions taken in the parts supply processes bringing significant reductions in the inventories held at the plant taken as unit of analysis as exhibited by Table 2. As the new system makes possible the final assembly of products in smaller batches in more frequent orders, relatively larger gains could be attained in the inventories of internally fabricated items for which more immediate rationalization measures could be taken.

Table 2 – Impacts on inventories.

| | Conveyor line | Work-cell |
|---|---|---|
| Lot size of outsourced parts [b] | 15 days | 2 days |
| Lot size of internally fabricated parts [b] | 1,200 | 320 |
| Internally stamped parts [a, b] | 100 | 14 |
| Internally enameled parts | 100 | 2 |
| Finished goods inventory [a] | 100 | 90 |

Notes: [a] Index number relative to line
[b] average figures

## CONCLUSION

The new assembly system enables small lot production and brought about sound conditions for the plant to operate much more responsively. As a matter of fact, the new production system makes possible the simultaneous production of a larger number of products: up to 8 different products against 3 in the previous system.

The implementation of the pilot cell and the overall production system change project that followed have evinced wastes and problems inherent to the conveyor line system. Furthermore, these experiences have demonstrated that work-cell based assembly system can be a key driver to accomplishing the CEPM-Br's strategic objective of enhancing operational excellence and reinforcing its competitiveness.

In the period considered by this case, the Brazil's currency has experienced a strong appreciation of about 10.5% against US dollar hitting seriously the export capacity of the manufacturers in this country. Even so, the efficiency gains that the adoption of the new production system brought about enabled to sustain the price competitiveness of the CEPM-Br's export-oriented products and prevented the transfer of its production to lower countries.

As for the "migration to work-cells approach" in itself undertaken in this case, given the significant gains and operational advantages observed in this initiative, its inherent potential, and the substantial competence developed by the involved project team, CEPM-Br's top management has already set plans to disseminate it in other manufacturing sites operated in Brazil involving the final assembly of other types of products. At the corporate level, CEPM is considering the application of this approach in manufacturing units located in other regions of the world as well. This further suggests the potential transferability of the work-cell based system.

Despite the potential of its broad scope application, it is important to remark that the adoption of this system should not be considered as a panacea. In fact, CEPM-Br managers acknowledge that depending on circumstances, the utilization of belt conveyor should be kept as its replacement by a work-cell based system may not be justified. This would be the case of production lines dedicated to a single standard product (or a narrow product family featuring minimum variation) where very specific processes required substantial capital investments in fabrication and assembly technologies, since, at least from the criterion of investment return, the shift to the cellular assembly approach would not justify.

With the bolstering of the operational capabilities in the assembly process, CEPM-Br management has now established the objectives to reintroduce low volume product models that had been removed from catalogue and launch new products with customizable elements. These plans were previously considered unfeasible given the rigidity of the conveyor lines used.

Considering the issue of broader diffusion of a production organization approach that resembles the cell production system developed by Japanese manufacturers, this case supports the transferability and feasibility of effective implementation of similar concepts and solutions in the setting of a consumer electric products industry in Brazil. However, while in Japan, the need to nurture more meaningful work environment and the pressure to agilely cope with introduction of new products induced by the trend of product life cycle shrinking are underlined among the primary motivations to adopt cell production system, in the case of CEPM-Br has prevailed the concerns to build a more cost efficient system that enables production in smaller lots and to improve quality of conformance.

Nevertheless, although lack of labor is not a constraint in Brazil, CEPM-Br managers believe that working conditions should be resolutely improved to sustain the work-cells. As a matter of fact, improvements are being devised so that female workers can also be employed in the main assembly process, a more ergonomic cart is under development, and the wage system was revised to compensate workers according to the skills and knowledge required in the new production system.

## ACKNOWLEDGMENT

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## Biography

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**Instructions**
Three copies of the manuscript and a labelled disk or a CD should be submitted. The article should be prepared using a A4 paper size (ISO 210 x 297 mm) in double line spacing with wide margins, and Times New Roman font 12 points, justified. Articles should be between 4,000 and 8,000 words in length (papers below or exceeding this limit will not be considered for reviewing). The following sequence is suggested (paper structure): title; abstract; keywords; introduction; main text and subject; conclusions; acknowledgements when applicable; and references.

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A title not too long should be provided. The title should precisely represents the subject of the paper in times New Roman font 14 points, all caps and centred.

**Authors Affiliation and Biography**
All authors not be included whose details must be printed on a separate sheet and the author should not be identified anywhere else in the article.
A brief autobiographical note (about 100 words) should be supplied including full name, affiliation, e-mail address and full international contact details.

**Abstract and Key words**
Authors must supply an abstract (100-200 words). Up to 5 keywords should be included which encapsulate the principal subjects covered by the article.

**Introduction**
The introduction should contain information intended for all readers of the journal, not just specialists in its area. It should describe the problem statement, its relevance, significant results and conclusions from prior work and objectives of the present work.

**Research Methodology**
It should be clearly described under a separate heading.

**Headings**
Headings must be short, clearly defined and not numbered. Sections headings should be typed bold-face, all in capital letters, flush with left-hand margin. Leave one line before and after headings. Subheadings should be typed bold-faced, flush with left-hand margin and only the first letter should be capital. Notes or Endnotes should not be used.

**Main Text and Subject**
Times New Roman font 12 points, justified. Paragraphs should not have any space indention.

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Figures and tables must be included in the main text and must be individually numbered and captioned with a brief title They should be provided both electronically and as good quality originals and must be black and white with minimum shading and numbered consecutively using Arabic numerals. Captions should be put below figures and above tables. Leave one line before (tables) or after (figures).

**Equations**
Equations should be typed flush with the left-hand margin and numbered consecutively with number in brackets on the right. Leave one line above and before equations.

**References**
References to other publications should be complete and in Harvard style. They should contain full bibliographical details and journal titles should not be abbreviated. For multiple citations in the same year use a, b, c immediately following the year of publication. References should be shown within the text by giving the author's last name followed by a comma and year of publication all in round brackets, e.g. (Fox, 1994). At the end of the article should be a reference list in alphabetical order as follows:

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surname and initials of author(s) year by brackets title, journal, volume, number, pages, e.g. Coughlan, P. and Coghlan, D. (2002) Action Research for Operations Management. International Journal of Operations and Production Management, Vol. 22, No. 2, pp. 220-240.

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