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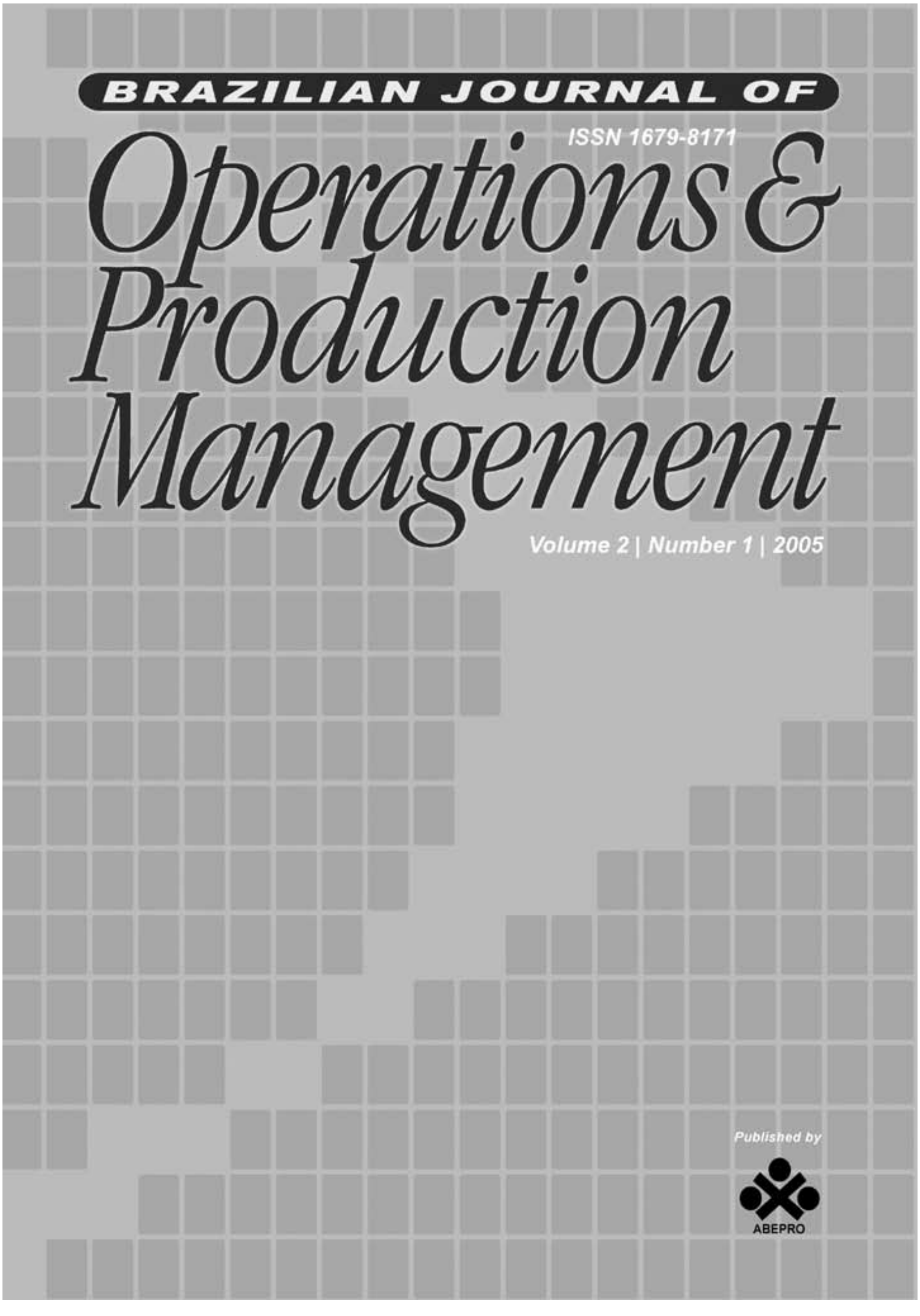

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Editorial Introduction

Finally, after some changes in the chain of command of ABEPRO (the Brazilian Production Engineering and Operations Management Association), we have managed to publish the first issue of volume 2 (2005) of the Brazilian Journal of Operations & Production Management. A number of persons should be acknowledged in this effort, especially those who work with ABEPRO. They are: Paulo Selig, current president, Maria Rita Assumpção Alves, and Osvaldo Luiz Gonçalves Quelhas. Moreover, special thanks are due to Adiel Almeida, from UFPE, Marcius Carvalho from CenPRA, and Sílvio Pires from UNIMEP. Their support and contributions to the editorship have been excellent.

For this issue, we had nearly twenty submissions (including a couple of papers submitted to volume 1, 2004, which were already in the process of double-blind review). Five of them were rejected up-front by the editor and editorial advisory board because they were out of the scope or their contents were not strong enough to be included in the review process, either by their weak theoretical background or poor research methodology. Six papers were rejected by the referees and the remaining still in the review process due to a number of reasons (e.g. adjudication). Concerning the result of the present issue, three competitive papers from Brazil, one paper from Portugal, and one paper from Brazil and the UK were accepted.

The accomplishment of this first issue would not be possible without the work of our editorial review board. I would like to take this opportunity to acknowledge them. They have provided the journal with a high level evaluation, surely contributing to the authors and the referral process. The reviewer's insightful comments have helped the authors of the selected papers to enhance their articles.

I hope the readers find the articles a useful source within the scope of production engineering and operations management. Please enjoy them.

In this Issue

Once again we have a rich mixture of qualitative and quantitative approaches as well as theoretical and empirical research in this issue. The first paper begins with an empirical article from Portugal, by António Carrizo Moreira on new product development at inter-firm level. The paper presents four case studies to exemplify the supplier's perceptions to inter-firm product development involving differently endowed firms. Next, Maysa de Magalhães and Antonio Fernando Costa present an economic-statistical model for a control chart. Considering the proposed model, a sensitive analysis is undertaken. A quantitative data analysis is also considered in the third article by Sueli Mingoti and Otaviano Neves. The objective of the paper is to present estimators for the variance of autocorrelated processes by using geostatistics methodology. The study is complemented by a Monte Carlo simulation study showed that the proposed estimators have good performance. Then, Rogerio Serrão and Paulo Dalcol discuss the alignment of actual manufacturing flexibility, considering the scope and achievability factors of five flexibility dimensions, and important aspects of management priorities and manufacturing performance. The article includes a field work involving five small companies. In our final article, Flavio Fernandes, Moacir Godinho Filho e Maurice Bonney, from the University of Nothingham, presents a proposal for integrating materials flow, production control and quality control. A case study is carried out from which results shows that the proposal contributes effectively to operations management at the shop floor level.

This issue concludes with some call for papers of international conferences on operations management and production research.

The journal expects to count on the research community by considering the journal as the outlet for publication of their research work mostly related but not limited to the research areas defined by ABEPRO[1].

Paulo A. Cauchick Miguel
Editor of BJO&PM

[1] Production Management; Quality Operations; Economic Management; Ergonomics and Work Safety; Product Development; Operational Research; Strategy and Organizations; Technology Management; Information Systems; Environmental Management; Education issues in operations management.

Supplier-buyer Collaboration in New Product Development: Four Case Studies Involving SMEs

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Abstract

New product development at inter-firm level is clearly an important topic for researchers and managers. Although many papers have reported the importance of collaboration in NPD the collaboration involving partners with different technology endowments and how many small firms have managed to achieve a status of reciprocity have remained unaddressed. In this exploratory study four multinationals and sixteen suppliers were visited and their top executives interviewed to determine the key success factors of collaborative product development as perceived by suppliers. Four case studies were prepared in order to exemplify the supplier's perceptions to inter-firm product development involving differently endowed firms. The main findings are clear: suppliers and clients have different perspectives and play different roles due to the bargaining power exercised by the latter and by the *fight* for reciprocity of the former.

Keywords: product development, collaborative strategies, supply chain management, co-operation, Portugal

Introduction

Although the management of the supply chain is an important aspect of firm's competitive advantage, only recently proper attention has been given to New Product Development (NPD) activities as part of this supply chain.

Collaboration between two or more organisations is expensive, resource intensive and risky (Hartley et al., 1997). Effective integration of suppliers in collaborative product development (CPD) can yield some benefits as well (Handfield et al., 1999), namely achieving reduced cost at product development, decreased risk of failure and reduced time taken in product development.

Most of the research on CPD is the outcome of experiences carried out involving multinational players in technologically advanced settings. Despite the widespread

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recognition of the success factors and of the reasons for failure in collaborative approaches, little research exists on the factors that affect the involvement of small and medium-sized firms with limited technological endowments. Thus, it is the aim of this paper to fill this gap addressing the main key factors that affect supplier's involvement in collaborative product development. An exploratory study was performed using data from 16 suppliers and four case studies have been prepared to address this context-specific situation in order to answer two questions. First, what key factors lead producers to involve their suppliers (SMEs) in CPD? Second, how are small suppliers responding to evolving challenges of their buyers?

The Development of New Products

The study of new product development (NPD) has been multidimensional in nature, highly complicated and has involved holistic and soft systems approaches.

The literature indicates that differences in NPD performance occur due to differences in availability of resources, in firms' size and organisational specialization. Lindman (2002) contends that the firm's ability to take advantage of emerging opportunities is a matter of management skills availability and the corresponding ability to create and apply new knowledge.

Cooper (1979) was one of the firsts researching on performance factors in single products. He found that excellent market knowledge, marketing skills, effective product launch and an adequate technical and production synergy were the most important factors of superior performance.

The importance of new product development for businesses was clearly put forward by Griffin (1997a). She demonstrated that while 49% of sales growth at successful companies comes from new products only half of that growth comes from less successful firms at launching new products. These results support Urban and Hauser's thesis (1993) that asserts that successful performance is highly connected with proper launching of new products and marketing performance.

Urban and Hauser (1993) studied the success factors and the reasons for failure in launching new products, as shown in Table 1. Although very relevant in the business arena, the main problem with the success factors stems from the definition of success, which is very ambiguous. For example, a failure in launching a new product may result in new knowledge that is used profitably in subsequent launchings. As a consequence, success may depend on the goals and objectives defined, on the appraisal perspective and on the lack of control of exogenous factors.

The identification of key success factors has been controversial with Ernst (2002) questioning some results obtained by NPD gurus, especially due to methodological problems. Based on a survey of the literature, Ernst (2002) found that the following five key success factors in new product development influences the firm's performance:

Table 1 – New product success factors and reason for failure.

Success Factors	Reasons for Failure
Global focus - world wide strategy	Small market
Short *Time-to-market*	Forecasting errors
Match customer needs	Not new/innovative products
High value to the customer	Insufficient return on investment
Innovative products	Organizational problems
Technical Superiority	Lack of cross-functional co-ordination
Screening, analysis and decision support system	Changes in customers tastes
Favourable competitive environment	Poor strategic positioning
Adequate firm-industry fit	Inadequate support to distribution channel
Cross-functional communication	Technological shifts during product development
Top management commitment	Disciplined new product development process
Disciplined new-product process	Changes in the competitive environment
Dynamic development department	Poor after-sales service
Avoid unnecessary risks	
Quality and customer satisfaction in all phases	

Source: Urban and Hauser (1993).

the NPD process, the organization of that NPD process, the managerial culture, the top management commitment and the NPD strategy.

The NPD literature is varied and multifaceted, which makes it difficult to select an appropriate body to rely on. Thus, taking into account the five above-mentioned key success factors some selected articles are put forward on Table 2. Clearly, Cooper and Kleinschimdt (1995; 1996) approach NPD success factors extensively. After analysing 48 characteristics in a written questionnaire involving 135 industrial firms in Canada, USA and Europe they concluded that:

- High quality NPD process involves: a) quality of process execution; b) completeness and thoroughness of the process; c) an emphasis on pre-development activities; d) a sharp, early product definition; e) a tough go-kill milestone; f) the flexibility of the process; and g) a strong market orientation;
- High quality NPD development teams involve: a) a dedicated project leader; b) frequent communication and team meeting; and c) efficient decisions with minimum bureaucracy;
- NPD cross-functional teams involve: a) assigned teams of players; b) a multifunctional team; and c) a project leader and a team accountable for all facets of the project;
- Senior management commitment in NPD success involves: a) participation in go/ kill decisions; b) allocation of necessary resources to NPD; c) identification of NPD annual objectives; d) NPD measures; e) adequate R&D budgets; and f) personnel resources; and
- High quality NPD strategy: a) definitions of goal for NPD programme; b) definitions of roles and business arenas of new products; and c) long-term projects and focus.

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Table 2 – Selected literature on NPD key success factors.

NPD Process	Cooper and Kleinschmidt, 1993b; 1995; 1996; Athuahene-Gima, 1995; Balbontin et al., 1996; Griffin, 1997b
Organizational Aspects	Cooper 1994; Cooper and Kleinschmidt, 1993b; 1995; 1996; Song and Perry, 1997; Song et al., 1997; Balbontin et al., 1996; Griffin, 1997b
Cultural Aspects on NPD	Cooper and Kleinschmidt, 1993b; 1995; 1996; Barczak, 1995; Song and Perry, 1997; Yap and Souder, 1994;
The Role and Commitment of Senior Management	Cooper and Kleinschmidt, 1993a; 1995; 1996; Balbontin et al., 1999; Johne and Snelson, 1988; Song and Perry, 1997; Yap and Souder, 1994;
NPD strategy	Cooper and Kleinschmidt, 1995; 1996; Griffin, 1997b;

Suppliers' Involvement in New Product Development

Collaborative approaches have been receiving a growing attention in the technical literature, with global competition and technological change pointed as the main drivers of these approaches. However, when NPD is included in collaborative approaches the traditional perspective of network of firms is in jeopardy because the competitiveness of several companies along the supply chain is differently affected due to the radical, interactive and multifaceted nature of CPD.

Although the reasons behind partners' involvement in partnerships vary extensively, the main issue for the producer in inter-firms relationships is the progressive integration of some key suppliers, which implies a serious commitment among partners in terms of *shared* competitive attitude (Bertodo, 1991; Clark, 1989). This attitudinal change paves the way for cooperative approaches to stand out as an alternative to antagonistic approaches. In this way, vertical cooperative strategies allow that the supplier's competitive advantages complement the client's ones and therefore are synergistic in nature.

Lamming's (1993) work gave supplier-client relationships a new life. He demonstrated that this relationship is evolutionary and cumulative in nature and depends on the mutual involvement of both the supplier and the client, the atmosphere of both firms' interaction and the environment in which the relationship takes place.

Lamming (1993) made public that the challenge of product design integration along the supply chain depends on multiple factors, not just in the two partners' convergent interests as originally thought.

Clark and Fujimoto (1991), Imai et al., (1985) and Womack et al. (1992) gave new light to NPD studies emphasising the importance of the different parties involved in NPD and addressing the importance of cross-functional, inter-firm product development

The shortening of the cycle time as a means of introducing new products more quickly into the market gave the involvement of suppliers in the design phase a fundamental importance. Clark (1989) concluded that supplier's involvement in the design phase and in problem resolution were critical in CPD. Suppliers' engineering competencies are also important: they influence NPD scope and project quality. Clark (1989) proposes not only that suppliers get involved in the initial phase of the product development, but also that both suppliers and clients base their relationship on what he called *reciprocity*: the clients should nurture their suppliers' competencies in order for them to assume some critical tasks in the development process. Wheelwright and Clark (1995) go even further defending that the development of product design competences is of fundamental importance in the long run of industrial companies' competitiveness.

Liker et al. (1995) demonstrated that the involvement of first-tier suppliers in co-design activities has positive impacts on NPD performances in terms of cost, quality and lead times.

Parnership activities in upstream activities involving NPD have traditionally followed two strands: the Japanese and the western style (Dyer and Ouchi, 1993; Liker et al., 1996). There are clear misunderstandings about the transfer of best practices from Japan to the Western world. As Fujimoto (2001) and Dyer (1998) demonstrated, a long-term relationship setting is missing when applying procedures as cost control and profit and information sharing.

Based on the nature of cooperative buyer-supplier relationships characterised by concepts such as trust and mutual dependence, Zirpoli and Caputo (2002) proposed seven principles for implementing buyer-supplier relationships:

1. The OEM should set the rules of the supply relationship in order to organise this vertical market;
2. There should be a preference for a long term obligational contractual relation instead of an arm's length contractual relation;
3. The use of techniques such as target costing, target pricing and value engineering are important means to implementing a fair distribution of relational quasi-rents;
4. The OEM should have a small number of suppliers for each type of part in order to provide them with enough production volume so that they can invest in R&D;
5. There must be competition between suppliers;
6. Sharing and managing information and knowledge is crucial for OEMs to impose transparency; and
7. Reputation should be one of the most powerful discipline mechanism for managing the supplier-buyer relationship.

As collaborative product development involves internal and external actors and functional areas, firms need to intensify cross-functional communication among the network of suppliers in order to increase speed-to-market responsiveness and flexibility in the creation of new products (Imai et al., 1985). As a consequence, hierarchical relationships with suppliers are giving way to more collaborative approaches.

Taking into account the extent to which suppliers are involved in product development, they may be divided in four categories according to the type of products they supply (Clark and Fujimoto, 1991; Lamming, 1993): as *Supplier-proprietary parts*, as *Black-box parts*, as *Grey-box parts* and as *Detail-controlled parts. Supplier-proprietary parts* are standard components whose development is the supplier's responsibility. Their influence in downstream activities in the value chain is small. *Black-box parts* are components whose functional and performance requirements are specified by the customer, but whose engineering details are handled by the supplier. This allows the producer to use the supplier's knowledge and engineering base while maintaining the technological control over the end product. *Grey-box parts* are similar to black-box parts but the producers control a great deal of the parts' internal functioning. Finally, *detail-controlled parts* are components whose technical and design requirements are carried out entirely by producers. In this case the involvement of the suppliers is perfectly passive since the whole decision process is the producer's responsibility.

Clearly, the supplier is not *de facto* involved in product development neither in the *supplier proprietary parts* nor in *detail-controlled parts*. In the first case the "relationship" is almost null due to the fact that *supplier proprietary parts* can be viewed as off-the-shelf components. In the second case the supplier's involvement is perfectly passive since the whole decision process is the buyer's responsibility.

An important tacit aspect in this typology is the degree of involvement of the suppliers, which is related with two reciprocal aspects: the supplier's capability in assuming NPD responsibility and the client's commitment in a bilateral relationship. Kamath et al. (1994) criticize this tacit relationship defending that only some first-tier suppliers are *de* facto partners.

Kamath and Liker (1994) approached the supplier-client relationship from the perspective of the suppliers addressing the evolutionary dynamics in inter-firm relationships. The main characteristics of those relationships are shown in Table 3. As can be seen, the supplier only assumes the design responsibility in mature and partner phases. Although there is a shared responsibility in the child stage, the supplier has to follow detailed information and specifications imposed by the client, which implies that its role in NPD process is incipient.

Suppliers' Involvement in Collaborative Product Development: Potential Benefits and Critical Factors

The management of NPD process at inter-firm level is a key element of competitiveness. It involves the management of different a) strategic interests; b) knowledge and

Table 3 – Supplier roles in product development.

	Contractual	Child	Mature	Partner
Design Responsibility	Client	Joint	Supplier	Supplier
Product Complexity	Simple Parts	Simple Assembly	Complex Assembly	Subsystem
Specifications Provided	Complete Design	Detailed Specifications	Critical Specifications	Concept
Supplier's Influence on Specifications	None	Present Capabilities	Negotiate	Collaborate
Stage of Supplier's Involvement	Prototyping	Post-concept	Concept	Pre-concept
Component-testing Responsibility	Minor	Moderate	Major	Complete
Supplier's Technological Capability	Low	Medium	High	Autonomous

Source: Kamath and Liker (1994).

technological capabilities; c) perceptions of the external environment; and d) collaborative involvements. Therefore, the integration of the NPD process implies shared challenges at R&D level as well as common efforts at new product development level, which according to Nishiguchi (1994) involves an inter-firm co-specialisation among participants.

The successful integration of suppliers in NPD involves many variables (Kamath and Liker, 1994; Handfield et al., 1999): the tier structure, the responsibility for design, the timing of supplier involvement, intellectual property agreements, inter-firm communication, membership on project team, supplier's capabilities, component-testing responsibility and technology risk assessment. It is not strange then to assess successful supplier integration in terms of new product development process.

Many benefits have been mentioned in support of the client-producer relationship and consequently only the most relevant ones will be mentioned. In terms of collaborative development Littler et al. (1995) state that frequent inter-firm communication, building trust, establishing partnership equity and employing a collaborative champion beneficial for NPD process. Hartley et al. (1997) found that the longer the time of supplier involvement the more the perceived contribution to new process design. Wasti and Liker (1997) concluded that early supplier involvement allows more focus for *Design for Manufacturing* and an improvement in the inter-firm design process.

The drawbacks of supplier-client partnerships in the supply chain have not been widely disclosed. Mohr and Spekman (1994) state that the evidences of superior competitiveness for both partners are much more implicit than explicit. Hartley et al. (1997) concluded that the adoption of generic techniques as suggested in the technical literature does not necessarily lead to a shorter product/project development lead-time. Littler et al. (1998) question the design collaboration asserting that in 40% of the companies studied the collaboration turned the NPD process more expensive, more complicated, less efficient, more difficult to control and harder to manage. Terwiesch et al. (1996) defend that CPD only has financial interest when the suppliers are large companies. Reciprocally, it is not interesting for suppliers of small size. Finally, Eisenhardt and Tabrizi (1995) demonstrated that the suppliers' involvement in the reduction of product development lead-time was only interesting in mature industries.

This paradox between benefits and inconveniences leaves plenty of room to address the understanding of the critical success factors that make the supplier-client relationship well succeeded at NPD level.

An important aspect of the benefits, inconveniences and key factors of inter-firm relationships should be stressed: they represent the outcomes of researches carried out in large, multinational firms, which cannot necessarily be "exported" to other country-specific contexts as is the case of Portugal, a *less-favoured* European *region* with a myriad of SMEs. Nevertheless, since Portuguese companies have to face enlarged markets and to compete with very large, stronger companies, this kind of research can serve as reference of analysis.

Objectives and Research Methodology of the Study

The NPD process in collaborative relationships has many intricacies as mentioned in previous sections. Unfortunately, it has remained unexplored in the Portuguese context where the presence of a myriad of SMEs with varied resources and performances makes it difficult to exploit experiences from different economic settings. Thus it was decided to study the NPD process in Portuguese companies in order to set the ground for subsequent studies addressing the inter-firm partnership in *less-favoured* regions.

The main purpose of this paper is therefore to address the main key factors that make the supplier-producer relationship well succeeded in the supply chain, taking into account Portuguese firms embedded in an international setting. Thus, an exploratory study involving industrial companies and their direct suppliers was performed in order to test the critical factors found in the literature. Moreover, case studies have been used to address context-specific factors. Therefore, one objective of this work is not to obtain a complete list of those key success factors, but rather to find out the main characteristics that make the supplier-client relationships well succeeded in the Portuguese setting. Another objective is to pave the way for subsequent studies dealing with the intricacies of NPD in a *less-favoured* setting involving small and medium-sized firms.

To define the sample two subsets of firms were created: the producers and the suppliers. Due to the consequences of the globalization process at firm level, it was decided to include industrial companies under the "influence" of this process. Moreover, given the structural importance of the automobile and electronics clusters firms of these industries have been included. As a consequence, the first subset of firms - the producers - was formed taking into account foreign firms in Portugal and the second group - the suppliers - was composed of indigenous companies supplying those multinational firms in which the NPD process was to be followed on the Portuguese suppliers.

The identification of the producers was done through secondary information and involved the selection of the two largest firms of each industry. The identification of the suppliers was based on information released by the producers during the interviews. It was decided to select four suppliers for each producer selected. This led to a final selection of four producers and sixteen suppliers.

The gathering of data was done through *in loco*, semi-structured, tape-recorded interviews at the producers and at the suppliers' sites. The use of semi-structured interviews allowed the researcher to explore the interviewees' points of view as well as to understand the NPD process at inter-firm level, which would have been difficult to obtain through a quantitative study. The aggregation of results was done *a posteriori*.

Due to the huge differences found among suppliers, in terms of resources and behaviours, four case studies have been selected that address successful examples of suppliers' involvement in the development of the client's CPD process.

Results

This paper aims at exploring the most important aspects of the supplier involvement in the development of its client's products. The findings discussed below are derived from an on-going study of NPD practices of Portuguese firms. The paper reports on the initial tranche of interviews and case studies from which different types of firms and different specific situations are assessed. The four suppliers under study are identified here as ***Alpha***, ***Beta***, ***Epsilon*** and ***Lambda*** for confidentiality reasons.

Case 1: Alpha

It is a family business producing stamped metallic parts for the electronics cluster. It has around 30 employees and supplies several multinational companies of the electronics industry. Its Engineering and Quality department has 7 resident engineers and three of them work closely with the largest client of stamped metallic parts. The company has been co-operating with its clients in the development of new products. The company is undergoing the ISO 9000 certification process and its two main clients consider *Alpha* as *preferred supplier*.

Alpha is involved in CPD process after the product concept phase and before the prototype is built. There is plenty of information exchange with its main client in terms of cost, product quality and production process. JIT delivery is currently on practice (*Alpha's* main client is less than a mile away from *Alpha's* premises.

As *Alpha* produces metallic stamped piece-parts, it usually follows the client's specifications and the proposals of new products. The creation of brand new solutions is quite difficult: stamped metallic parts are one of many components of the car-radio (the client's final product), that it is also part of the car dashboard, which is designed and

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developed by project teams of car manufacturers. Consequently, the company is committed to satisfying the car-radio producer's demands in terms of price, delivery time and product quality, in order to strengthen supplier-client relationship.

Alpha foresees an evolution towards a product-specialist/partner relationship as being *difficult* due to the following facts a) car-radio development decisions take place two levels downstream in the value chain; and b) car-radio metallic parts are not considered as *strategic* in the design phase. Then, it can be argued that although *Alpha* has a reactive product development type due to the non-strategic nature of the component, it has managed to abandon a dependent strategy and to increase value for its clients in the supply chain.

Case 2: Beta

Beta is a SME with 25 employees and produces prototypes and specialized solutions based on automation for a diversified group of clients. Its main customers belong to the automobile and electronics industries. Its *R&D department* has 7 people, being four of them resident engineers.

Since its start up *Beta* has managed to diversify its customer base in such a way that it produces a wide range of automation equipment/solutions for several multinational companies in Portugal and abroad. Its main competitive advantage rests on the *competence to solve its customers' problems*.

Beta's technological strategy is underpinned in the creation of new products and has as starting point the clients' technological needs. *Beta* claims that they systematically use reverse engineering and benchmarking tools to improve its technological base. Its approach is quite simple: the NPD process begins with the client's formal request and involves the creation of a cross-functional, inter-firm team in order to gain lead time, knowledge and to avoid future technical problems.

Case 3: Epsilon

Epsilon manufactures plastic components for the automobile, telecommunications, electronics and home appliances industries. Epsilon has around 400 employees and a sales volume around 20 M €. Its *development and engineering* department has 39 people, being 28 of them resident engineers. It holds the ISO 9000 registration. It has strong production capabilities and its production process fully automated. Its core business is the design of plastic injection parts and is technically considered one of the best firms in the industry.

Epsilon has managed to evolve in the NPD process. It creates new concepts with the clients' involvement, which clearly represents an important evolutionary step in *Epsilon's* technological ladder.

The firm's technology base evolved from a passive to an active product-engineering base because the firm has managed to accumulate knowledge in its relationship with its clients in such a way that it enabled *Epsilon* to create new concepts for carmakers according to their volumetric constraints.

Epsilon has managed to design and produce dashboards for two large German automakers. This means that *Epsilon* has managed to evolve from an OEM to an Own Design Manufacture (ODM) approach. In the future it is expected that the firm can evolve to deeper, more intertwined relationship in the supply chain due to their design capabilities.

Epsilon intervenes in the CPD process in the product concept phase where it is involved in the client's corporate development project team, which includes external consultants and other components suppliers. Specific responsibilities are affected to all participants and despite Epsilon responsibilities in the design of dashboards, Epsilon's client hold the final authority for design. Apart from a non-disclosure agreement signed between Epsilon and its main client, there are no other intellectual property agreements signed.

Case 4: Lambda

Lambda is a large firm that produces industrial and starter batteries for the automobile industry. It has more than 400 employees and produces batteries not only for large automakers but also for the original equipment spares (OES) market, which exposes *Lambda* to a global competitiveness. *Lambda* has been very active in R&D activities: it has been granted a world patent and has signed several technology-based joint ventures. Its *R&D and product engineering* department has 45 people, being 30 of them resident engineers

It holds the ISO 9001 registration and has a strong R&D department that underpins the participation in the development of new products in co-operation with its main clients. Its technological accumulation process has allowed the firm to leapfrog from OEM to ODM to Own Brand Manufacture (OBM) activities. *Lambda* produces and commercialises its own brand name for the OES market.

Lambda has managed to evolve to an active stage in the inter-firm NPD process. It has developed a partnership with a German engineering firm to design batteries for a German automaker according to their vehicles energetic needs. This active participation in the NPD process has allowed *Lambda* to take advantage of this important strategic positioning since it is closer to its client's core decision centre in the product development phase. In order to maintain its relationship in the CPD process Lambda has to reach target costs imposed by the client as well as quality and delivery targets. As Lambda produces a commodity-like product the firm is only involved after the client concept has been specified.

Discussion

In order to give a broader perspective of the four case studies discussed above, Table 4 shows the main suppliers characteristics and Table 5 presents their project management processes.

Only *Epsilon* and Lambda, which are larger than the other two firms and have a previous experience in collaborative activities, have managed to reach the mature stage proposed by Kamath and Liker (1994).

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Table 4 – Suppliers' main characteristics.

	Alpha	Beta	Epsilon	Lambda
Collaborative Experience	No	No	Yes	Yes
Prior Involvement with Client	No	No	Yes	Yes
Quality Registration	In Process	No	Yes	Yes
JIT Relationship	Yes	No	Yes	Yes
Types of Parts	Supplier Proprietary Part	Detail Controlled Project	Grey Box Part (Aesthetic)	Supplier Proprietary Part
Design Responsibility	Supplier	Supplier	Supplier	Supplier
Design Authority	Joint	Joint	Customer	Supplier
Product Complexity	Simple Assembly	Entire Sub-system	Complex Assembly	Simple Assembly
Specifications Provided	Detail Engineering	Concept	Concept	Concept/Early Product Design
Supplier Information Specifications	Collaborate	Collaborate/ Negotiate	Negotiate	Collaborate
Stage of Supplier Involvement	Early Product Design	Pre-concept Concept	Concept	Concept/Early Product Design
Component Testing Responsibility	Complete	Complete	Complete	Complete
Supplier Technological Capability	Medium	High	Autonomous	Autonomous
Type of Relationship	Child/Contractual	Contractual	Mature	Mature/Partner

While *Epsilon's* product can be characterised as a *grey-box* part, *Lambda's* is a *black-box* part. In both firms the supplier-client relationship is based on the co-specialization of both partners.

Beta still has a contractual relationship due to its project-by-project involvement. On the other hand, *Alpha* is still in the child/contractual phase and its evolutionary perspective towards a mature relationship is expected to be difficult due to the product that it manufactures.

The type of product is responsible for wide differences in inter-firm relationships. Suppliers are in better conditions of having a symbiotic relationship with their customers when products are characterised as *black-box* and *grey-box* parts. Inversely, whenever products are characterised as *supplier-proprietary* parts the relationship seems to be condemned to a contractual/child one.

Beta is in a very specific situation because it is closer to a project-based relationship whose purchase is non-repetitive in nature and therefore they will hardly achieve the mature/partner relationship.

Interestingly, quality is felt differently felt in all firms. While Epsilon and Lambda are certified according to ISO 9000 standards (Alpha will soon apply for it), Beta has no intention to register according to the ISO 9000 standards. This difference is explained by Beta's project orientation *vis-à-vis* the product orientation of the remaining suppliers.

Table 5 – Project management process.

	Alpha	Beta	Epsilon	Lambda
Characterisation of Process	Phases and Gates	Contract driven, but oriented to client	Customer-focused multi-functional team	Phases and Gates
Dominant Characteristics	Cross-functional team with project manager that oversees entire project	Project-team focus with dominant project manager	Project-team focus with dominant project manager	Cross-functional team involving technology transfers to other sister units. Project manager that oversees entire project
Key Control Mechanism	Project manager. Review meetings each two months.	Contract. Project manager lead relationship between Beta, suppliers and client.	Senior product manager. Senior management reviews at milestones.	Senior product manager. Senior management reviews at milestones.
Primary Performance Drivers	Quality control and delivery reliability.	Delivery reliability. Functional Conformance of Prototype. New product support.	Volumetric and aesthetic conformance, speed in prototyping building, design capabilities and quality control.	Engineering functionality, delivery reliability and quality control.
Major Phases	Three-stage process (according to customer approval process)	Defined by customer process.	Five phases with tasks and milestones.	Seven phases with tasks and milestones.
Formality of Process	Standardised according to client's NPD introduction.	Flexible for each contract, but well defined procedures.	Highly formalised procedures according to management procedure document.	Highly formalised according to corporate handbook, which includes timing, cost, design information, quality approval for different milestones.

As shown in Table 5, although suppliers' project management tools and processes are varied only *Epsilon* and Lambda have highly formalised management procedures tuned with those of the buyers. This is a consequence of both the influence of the automotive industry management practices and of their past experience in collaborative agreements with their clients. On the other hand, *Beta's* project management tools are simpler and more internally focused.

The ***suppliers NPD capabilities*** are relatively homogeneous. All suppliers have managed to abandon dependent subcontracting behaviours and to be involved as product specialists. On the other side, the producers try to exploit the suppliers' know-how and resources. Although the NPD capabilities differ, with Alpha and Beta being categorised as reactive product specialists and Lambda and Epsilon as active product specialists, it is plausible to argue that the supplier-producer relationship in terms of NPD capabilities is based on the search of a wide reciprocity. Nevertheless, the product characteristics play an important role with key component suppliers (Epsilon and Lambda) better off than standard parts suppliers (Alpha).

The ***cooperation with suppliers*** in upstream activities is unbalanced: only in cases 3 and 4 collaborative relationships follow a win-win approach. In cases 1 and 2 the producer seems to be more interested in taking advantage of the supplier's co-specialization than in a long-term relationship. This difference may be explained by the type of product: while in cases 3 and 4 the repetitive nature of the product and the cumulative past experience in product development positively influences the supplier-producer involvement, in case 2 the sequential project-by-project nature of the product limits the product development involvement between players to a single project. In case 1, the reactive nature of the product-engineering involvement leaves the supplier in a serious disadvantage. In conclusion, the larger the strategic interests of the client in upstream activities along the value chain the larger the expected benefits of suppliers.

All companies confirmed the need and the importance of ***early involvement***, which was considered as a critical success factor because it allowed the suppliers to influence the design, to present solutions and to promote a long-term relationship.

If it is taken into account the stage of supplier involvement, the supplier's design authority and the supplier's product complexity it is possible to conclude that early involvement should be seen as the supplier's willingness to evolve in the relationship, which is very positive for the relationship: while suppliers still have incentives to innovate, the buyers still have room to improve supplier's efforts.

Paradoxically, ***inter-firm cooperation*** in the NPD phase between ***the suppliers and their suppliers*** is nonexistent, which clearly stresses the need of an integrative industrial strategy.

At ***strategic level*** suppliers and clients showed a congruent point of view. The involvement is notorious in the communication of objectives, planning and common projects, which helps both partners in the creation of a long-term involvement. NPD was facilitated by the fact that all the producers have considered that, although the core competencies belonged to the suppliers, the design for manufacturing was controlled by the producers, which allowed the latter to strategically control the participation of the suppliers.

Project management was also very important. The outcomes in the electronics industry and the auto industry were quite different. In the automobile industry there seems to be a larger complexity in terms of a) task specification; b) both partners' participation; and c) implementation periods, which may be explained by the complexity of the product and by the partners' co-specialization. The pressure in the relationship is very explicit when there are changes in the prototype phase and when there are delays in the production start up.

One problem seems unaddressed in the technical literature: when there are changes in an advanced phase of the project - close to the production start-up date - involving

a) changes in tools/equipment; b) costs related to those changes or; and c) potential delays in the project, the pressure between both partners dramatically increases mainly due to the bargaining power unilaterally exercised by the client.

It was intended to assess to what extent the producer played the ***coordinator's role*** and if the collaboration involved a ***reciprocity*** between both partners. All suppliers were unanimous in considering the producer as the coordinator of the relationship. Equally important, the suppliers mentioned that the producers should develop project management capabilities and simultaneous engineering competencies in order to improve the reciprocity of the supplier-producer relationship. On the other hand, all producers have a different opinion regarding coordination and reciprocity. They claim project management capabilities are not considered a strategic issue. Regarding reciprocity they claim that suppliers need to improve their technological capability and their allocation of resources to R&D activities in order to be reliable suppliers. The producers' perspective is clear: the coordination would be simpler if the suppliers' technological capability were stronger. That in turn would enable a reciprocal, smoother relationship in the supply chain.

The different point of views in both subjects can be explained by the different expectations of both players. The buyers are seen as natural product/project coordinators by their roles in the relationship: they "impose" quality policies, product specifications, target prices, NPD times, delivery times and technology strategies. As a consequence, it is not strange that suppliers, despite their competencies in production, quality, JIT delivery and NPD activities still see buyers as "paving the way" of the relationship. Consequently, reciprocity might be differently understood by both partners: for example, when changes in an advanced phase of the project are put forward by buyers, as above mentioned, suppliers feel that buyers exercise their bargaining power and blame them for not introducing the changes earlier and consequently for jeopardising the relationship. On the other hand if for example suppliers had been intensively involved in project management activities and if changes in advanced phase of the project needed to be done, would they claim lack of reciprocity? Clearly, transparency, reciprocity and coordination are difficult to manage when both firms have different interests.

Conclusions

This paper addresses the success and failure factors of Collaborative Product Development in a less technologically endowed environment involving SMEs. For such purpose, a qualitative study was deployed along the supply chain involving sixteen Portuguese firms, four multinational companies and the preparation of four case studies. The goal of this study was to *question* the conclusions obtained in different contexts involving small and medium-sized firms with "*limited*" technological endowments and to pave the way for a broader study.

The methodology allowed the exploration of knowledge obtained during the interviews, the clarification of doubts and the deepening of important aspects that would remain unanswered through the analysis of a quantitative study.

Generically, the involvement of suppliers in the NPD phase is more complex than the technical literature describes.

The four cases involved suppliers with different products and sizes. Nevertheless, there were not large differences among them in the willingness to collaborate in the NPD phase.

Alpha did not have any prior involvement with multinationals of the electronics cluster before they rooted their factories in Portugal. Although following a slightly reactive strategy due to the product type it manufactures, its successful relationship with its multinational clients stems from its technological competences. On the other side *Beta* departed from a pure dependent strategy and along time it managed to diversify its customer base. Its relationship with its clients is quite specific due to the nature of product it manufactures.

Epsilon and *Lambda* have been following a relatively similar path: their technological capability allowed them to be progressively more involved in CPD in such a way that they have managed to participate in the development of new products with their clients' corporate development department at headquarters level.

The interviews and the organisation of case studies led to the conclusion that the suppliers seek NPD collaborative approaches so that they can improve their competitive position *vis-à-vis* their clients.

Generically, it can be said that firms of the automobile industry are better tuned than the ones of the electronics cluster to the needs and difficulties of the NPD collaborative approach, which may be explained by the differences in industry maturity and the competitiveness of the auto industry.

Four successful case studies were presented. Clearly, a critical aspect in the development of a technological complementary is the suppliers' capacity in developing R&D competencies. Although the case studies showed evidence of the suppliers' clear commitment in developing their technological competence in order to abandon passive subcontracting behaviour and positioning themselves as product specialists, it is plausible to say that the client's role should not be underestimated: dynamic complementarities must be underpinned upon the involvement of both partners. As a consequence, broader studies addressing both partners involvement should be performed in order to understand their commitment in the relationship.

Subsequent studies should address the following topics in order to complement the ones covered in this article:

1. How buyers set the rules and organise NPD management; Using target costing, value engineering, quality policy mechanisms, ..?;
2. How buyers manage the intricacies of production capacity management in order to provide suppliers with production volume so that they invest in R&D; and

3. When differences between partners arise, what mechanisms are used to manage transparency in the relationship.

Although this exploratory study helps in understanding the supplier involvement in CPD process, it has three limitations. Firstly, the group of case studies was purposively selected to present different situations and do not correspond to an average result. Secondly, the type of product should be addressed carefully because key components suppliers and standard parts suppliers may have different types of involvements with their clients due to differences in strategic interests. Thirdly, the client's involvement should also be addressed. Some clients seem to be keener than others in tapping into the suppliers' competencies and consequently the search for reciprocity is differently *felt* along the value chain.

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Biography

António C. Moreira received the degree in engineering and the MBA from the University of Porto, Portugal and a Ph.D. degree from UMIST - University of Manchester Institute of Science and Technology, England. He has a solid international background in industry where he worked for a Dutch multinational firm in Germany as well as in Portugal. He also has experience as a consultant and as a researcher, where he worked at INESC Porto's Manufacturing Systems Engineering Unit. He has been academically involved since 1993. He is Assistant Professor at DEGEI (Department of Economics, Industrial Engineering and Management) for the University of Aveiro, Portugal.

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Economic-Statistical Control Chart Design: A Sensitivity Study

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Abstract

When an economic-statistical model for a control chart is considered the effect of the choice of the bounds on the average times until a signal on the cost for controlling the process, including the cost with non-conformities produced, and on the design parameters is a natural issue that arises. To have an idea of how the costs and the chart's parameters are affected by these bounds is an important guidance for the design of the control charts, that is, for the choice of the size of the samples, the intervals between samplings, and the factors used in determining the width of the control limits. A sensitivity analysis of the choice of these bounds on the cost and the design parameters is presented to the adaptive $\overline{X}$ chart.

Keywords: adaptive control charts, economic-statistical design, sensitivity analysis

Introduction

The design of control charts with respect to economic criteria has been a subject of interest during the last four decades.

Duncan (1956) first proposed the economic design of $\overline{X}$ control charts. Since then, various models have been proposed for a number of Shewhart-type chart. Literature surveys of related work are presented in Gibra (1975), Montgomery (1980), Vance (1983), and Ho and Case (1994).

One concern about economic design of control charts is that it focuses only on costs, but ignores statistical properties, and thus it is entirely possible to produce designs that are optimal in an economic sense but which may have very poor statistical performance (see, Woodall, 1986).

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Saniga (1989) proposed the economic-statistical design of control charts. His paper became the foundation in this area, and several authors have followed up on his work. McWilliams (1994) provided a Fortran program that enables user to determine economic, statistical or economic-statistical $\overline{X}$ chart designs. Saniga et al.(1995) presented a computer program for determining the economic-statistical design of a fraction defective or defects per unit chart. Montgomery et al.(1995) presented a paper on the economic-statistical design of the EWMA control chart, and a computer program for the paper is developed by Torang et al. (1995). All these papers are related to economic-statistical designs of control charts with fixed design parameters.

Many researchers have been working on the economic and the economic-statistical design of fixed parameters control charts (see, for example, Saniga and Montgomery, 1981; Rahim, 1989; Costa, 1993; Rahim and Costa, 2000; and the references therein).

In economic and economic-statistical designs, a cost fucntion is formulated taking into account the overall cost of controlling the quality of a process through a control chart. This function provides a device for selection of the design parameters, and for comparison between charts. In economic-statistical design, moreover, statistical constraints are imposed on the cost function, such as requiring a short average time for the control chart to signal a process deterioration or a long average time between false alarms.

In recent years, a new class of control charts has been proposed where the design parameters (sample size, sample interval and control limit coefficient) are allowed to change in an adaptive way, that is, one or more design parameters vary as a function of the process data. These charts are called adaptive control charts and they have proved to be more efficient than fixed parameters control charts in detecting small to moderate shifts in the process parameter being controlled.

While the statistical design of adaptive charts has been studied extensively, very little work has been done on economic and economic-statistical design of these charts.

Economic designs for variable sample size (VSS) $\overline{X}$ charts were studied by Flaig (1991) and Park and Reynolds (1994). Variable sampling interval (VSI) control charts were considered by Das et al. (1997), Das and Gosavi (1997), Bai and Lee (1998). Subsequently, Park and Reynolds (1999) developed an economic model for a variable sample size and sampling interval (VSSI) $\overline{X}$ control chart. Finally, De Magalhães et al. (2001) investigated the economic design of variable parameters (VP) charts, in which all design parameters are considered variable.

Prabhu et al. (1997) proposed an economic-statistical design for a VSSI $\overline{X}$ chart and De Magalhães et al. (2002) developed an economic-ststistical model for a VP $\overline{X}$ chart.

In this paper, we consider the economic-statistical model for the adaptive $\overline{X}$ control chart developed by De Magalhães et al. (2002).

Considering the proposed model, a sensitivity analysis of the effect of the choice of the bounds on the average time until a signal, when the process is in control and out of control, on the cost and the design parameters for the adaptive $\overline{X}$ control chart is presented.

There are three numbers that should be taken care of when designing a chart using an economic-statistical criterion: the overall cost, the average time until a signal, when the process is in control and out of control. The choice of the design parameters should be guided, qualitatively, by the following rationale: the overall cost and the average time to signal when the process is out of control should be minimized and the average time to signal when the process is in control should be maximized. Since these requirements might be incompatible, one is led to the sensitivity analysis in order to be able to arrive at a compromise.

To present the sensitivity analysis we need to introduce the VP $\bar{X}$ chart and the assumptions about the production process as well to furnish the expression of the expected cost per time unit.

Adaptive $\bar{X}$ Control Chart

Suppose that an $\bar{X}$ control chart having all design parameters varying adaptively is employed to monitor a process whose quality characteristic of interest (say, X) is normally distributed with mean μ and variance σ^2. The target value of the process mean is represented by μ_0. The process is in control when $\mu = \mu_0$ and out of control when $\mu = \mu_0 + \delta\sigma$.

To utilize a control chart the user should specify: the sample size (n), the sampling interval (h) and the coefficient values used in determining the width of the control limits (k). These parameters are the design parameters of a control chart.

In a fixed parameter (FP) $\bar{X}$ chart, the design parameters are kept fixed during the production process. The VP $\bar{X}$ control chart is a modification of the FP $\bar{X}$ chart (Costa, 1999). The design parameters of the VP $\bar{X}$ control chart considered can assume two values each as a function of the most recent process information. That is, the position of each sample point on the VP $\bar{X}$ chart establishes the size of the next sample, the instant of its sampling and the width coefficient of the control limits.

We denote the values of the sample sizes by n_1 and n_2, the sampling intervals by h_1 and h_2, and the coefficient used in determining the width for the warning and control limits by w_1 and w_2, k_1 and k_2, respectively.

Let LCL and UCL represent, respectively, the lower and upper control limits for a VP $\bar{X}$ chart. The interval (LCL, UCL) is partitioned into three distinct regions: (LCL, LWL); (LWL, UWL); (UWL, UCL); with $LCL < LWL < UWL < UCL$. Here, LWL and UWL represent, respectively, the lower and upper warning limits of the $\bar{X}$ chart. As in the case of FP control charts, a signal is produced when a point falls outside the control limits. In the same way as in the FP control charts, this signal can be false or true. An alarm is false when a point falls outside the control limits but the mean μ is equal to μ_0. In other words, the control chart signals erroneously the occurrence of an assignable cause.

Note that for each sample point $\bar{x}_j$, $j = 1, 2, \ldots$ twopossibilities will be provided for the warning and control limits (that is, $\mu_0 \pm w_i \sigma / \sqrt{n_i}$ and $\mu_0 \pm k_i \sigma / \sqrt{n_i}$, $i = 1, 2,$ respectively)

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because each design parameter can assume two values. Here, w_1 (with $w_1 < k_1$) and w_2 (with $w_2 < k_2$) denote the width coeficients of the warning limits and they are also design parameters.

In a general form, the functioning policy of the VP $\bar{X}$ control charts establishes the action that should be taken when the sample points are obtained. In particular, this policy can establish that a new sample should be taken and which design parameters values should be utilized for the next sample taking into account the information due to the samples until the present moment. In the model considered, the decision of which design parameters values should be utilized will depend only on the last sample value and in which region, of the control chart, the sample point falls. That is, the design parameters of the control chart vary in function of the most recent process information (for details see, De Magalhães et al., 2002).

The size of the first sample that is taken from the process when it is just starting or after a false alarm, is chosen at random, according to probabilities given below. If the sample was chosen to be large (small) it should be sampled after a short (long) time interval. During the in-control period all samples, including the first one, have probability p_0 of being small and $(1 - p_0)$ of being large, where

$$p_0 = P(|Z| < w_1 \ \ | \ \ |Z| < k_1) = P(|Z| < w_2 \ \ | \ \ |Z| < k_2) \quad and \quad Z \sim N(0,1) \tag{1}$$

The user might prefer to fix the size of first sample (large or small). If the time between occurrence of assignable cause is long (e.g., small λ) the $\bar{X}$ chart properties are independent of the size of the first sample.

Economic-Statistical Design Model for the Adaptive $\bar{\mathbf{X}}$ Control Chart

To control the quality of a process through a control chart costs are incurred. In the model considered (De Magalhães et al., 2002), the expected cost per time unit (*ECTU*) is utilized to analyse these costs. The *ECTU* is a function of the costs incurred in different phases of the production cycle and also a function of the design parameters of the control chart. The expected cost per time unit is minimized with respect to the design parameters of the control chart considered.

To develop the economic model, assumptions about the production process are made. These assumptions characterize the class of production processes to be analysed. Although several supositions have been made, different production processes can be yet appropriatelly modelled.

Assumptions: It is assumed that the samples are independent, and that the process starts in a state of statistical control with mean $\mu = \mu_0$ and later on, due to occurrence of an assignable cause, the process mean goes to $\mu = \delta\sigma$. The length of time the process stays in control is an exponential random variable with mean $1/\lambda$. That is, the assignable cause occurs according to a Poisson process, with a intensity of λ occurrences per time unit.

The process is not self-corrective. During the search for an assignable cause and/or during repair the process may continue in operation or not. The parameters μ, σ and δ are assumed to be known and the parameters to be determined are n_1, n_2, h_1, h_2, w_1, w_2, k_1 and k_2.

The Cost Model

Since the process considered is a renewal reward process (see, Ross, 1970), the *ECTU* can be written as the ratio of the expected cost per cycle *(E(C))* to the expected cycle time *(E(T))*, that is: $ECTU = E(C) / E(T)$.

In the computation of *E(C)* and *E(T)*, the expressions for some variables are dependent on the VP policy adopted.

The expressions for *E(C)* and *E(T)* are given by:

$$E(T) = \frac{1}{\lambda} + (1-\delta_1)E(T_{af}) + E(T_{fc}) + E(T_a) + E(T_{esp}) + E(T_R)$$

$$E(C) = \frac{1}{\lambda}C_0 + C_1[E(T_{fc}) + E(T_a) + \delta_1 E(T_{esp}) + \delta_2 E(T_R)] + YE(F) + W + E(C_{am})$$

Here, $1/\lambda$ represents the average time the process stays in control. $E(T_{af})$ represents the average time spent in the investigation of false alarms and δ_1 is an indicator variable, when the process continues in operation during the search of an assignable cause $\delta_1 = 1$, otherwise $\delta_1 = 0$. The expected time searching for false alarms $E(T_{af})$ is equal to the expected search time associated with a false alarm (T_0) times the expected number of false alarms *E(F)*. $E(T_{fc})$ represents the average time since the occurrence of a shift in the process mean until the chart gives a signal. The average time to analyze a sample is represented by $E(T_a)$. The average time to find an assignable cause is represented by $E(T_{esp})$, it is assumed that this time is equal to a specified time T_*. The average time to do a repair is $E(T_r)$ and also it is assumed to be equal to T_{**}. Note that T_* and T_{**} can count or not to *E(C)* because the expected cost of producing non-conformities while the process is operating out of control is dependent on whether the production process stops or not during the search for an assignable cause and/or during repair. These possibilities are represented by the indicator variables δ_1 and δ_2 ($\delta_2 = 2$, if production continues during repair and $\delta_2 = 0$, otherwise). C_0 and C_1 represent, respectively, the costs per hour due to non-conformities produced while the process is in control and out of control.

YE(F) represents the cost due to false alarms, where *Y* is the cost per false alarm and *E(F)* is the expected number of false alarms. To determine *E(F)* it is necessary to compute the expected number of samples taken during an in-control period. The expected cost of finding and eliminating an assignable cause when one existss is given by *W*; this quantity includes any downtime that is appropriate, and is assumed to be policy independent. The expected cost of sampling and inspection is given by $E(C_{am})$.

This is a general economic model (Lorenzen and Vance, 1986), the explicit expressions for each entry in *E(T)* and *E(C)*, for the VP chart considered, were developed by De

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Magalhães et al. (2002). The explicit expressions of $E(T_{fc})$, $E(T_a)$, $E(F)$, $E(C_{am})$ depend on the design parameters of the chart considered. In *ECTU*, the variables λ, δ_1, δ_2, C_0, C_1, T_*, T_{**}, Y, W are input variables.

Economic-Statistical Model

The speed of detection of a shift in the process mean determines the efficacy of the control scheme. That is, the agility of a control chart in detecting a shift is determined by the length of time to produce a signal.

Usually, the process starts in control and some time in the future a shift occurs in the process mean. This suposition was assumed in the model considered. When a process is in control, it is desirable that the mean time since the beginning of the process until a signal be long; this guarantee few false alarms. This mean time is denoted by ATS_0. The expression of the ATS_0 for the VP control chart is given by

$$ATS_0 = \frac{[h_1(1-p_{22})+h_2 p_{12}]p_0 + [h_2(1-p_{11})+h_1 p_{21}](1-p_0)}{1-p_{11}-p_{22}+p_{11}p_{22}-p_{12}p_{21}}$$

where

$$p_{11}(0) = P(-w_1 < Z < w_1),\ p_{12}(0) = P(-k_1 < Z < -w_1) + P(w_1 < Z < k_1)$$
$$p_{21}(0) = P(-w_2 < Z < w_2),\ p_{22}(0) = P(-k_2 < Z < -w_2) + P(w_2 < Z < k_2)$$

and p_0 is given by Eq. (1).

The *ATS's* expression for $\overline{X}$ control chart with variable parameters was developed by Costa (1999).

If the process is out of control, then the time since the shift until an alarm occurs should be short, because in such case the off-target condition can be detected quickly. This average time is denoted by *AATS* (adjusted average time to signal). The *AATS's* expression is given by

$$AATS = E(R) + E(S)$$
$$E(R) = \{h_1 - \tau_{h1}\}P(A = h_1) + \{h_2 - \tau_{h2}\}P(A = h_2)_z$$

$$\begin{aligned} E(S) = \{&[h_1(1-p_{22}(\delta)) + h_2 p_{12}(\delta)][p_{11}(\delta)P(A=h_1) + p_{21}(\delta)P(A=h_2)] \\ &+[h_2(1-p_{11}(\delta)) + h_1 p_{21}(\delta)][p_{12}(\delta)P(A=h_1) + p_{22}(\delta)P(A=h_2)]\} \\ &\times \frac{1}{1-p_{11}(\delta)-p_{22}(\delta)+p_{11}(\delta)p_{22}(\delta)-p_{12}(\delta)p_{21}(\delta)} \end{aligned}$$

$$\tau_{h_1} = \frac{1-e^{-\lambda h_1}(1+\lambda h_1)}{\lambda\left(1-e^{-\lambda h_1}\right)} \qquad \tau_{h_1} = \frac{1-e^{-\lambda h_1}(1+\lambda h_1)}{\lambda\left(1-e^{-\lambda h_1}\right)}$$

$$P(A=h_1)=\frac{h_1 p_0}{h_1 p_0 + h_2(1-p_0)} \qquad P(A=h_2)=\frac{h_2(1-p_0)}{h_1 p_0 + h_2(1-p_0)}$$

A criticism about economic designs is that they do not take care of relevant statistical properties, for example, the optimal design parameters selected by the economic model can allow an excessive number of false alarms (ATS_0) and long average time since the shift until a signal (long $AATS$).

To improve the efficiency of the control charts, mainly in the detection of small to moderate shifts of the target value (0.5 σ to 1.5 σ), was the primary reason in the development of adaptive control charts (see, for example, Costa, 1998; Costa, 1997; Costa, 1994; Prabhu et al., 1994; Prabhu et al., 1993; Runger and Montgomery, 1993; Runger and Pignatiello, 1991; Reynolds et al., 1990; Reynolds et al., 1988). In fact, the adaptive control charts brought significant improvements in the statistical performance of economic designs (Park and Reynolds, 1994; Prabhu et al., 1997; De Magalhães et al., 2002).

If during the optimization of $ECTU$, constraints are imposed on the expected time to signal when the process is in control (ATS_0) and out of control ($AATS$), this ensures that the required statistical properties are satisfied.

The constraints are $ATS_0 \geq l$ and $AATS \leq u$, where l is a lower bound to ATS_0 and u is an upper bound to $AATS$. The design parameters of the economic-statistical model for the VP $\overline{X}$ control chart are obtained solving the optimization problem

$$\min\ ECTU$$
$$subject\ to \begin{cases} ATS_0 \geq l \\ AATS \leq u \end{cases}$$

Sensitivity Analysis – A Case Study

When an economic-statistical model is considered the effect of the choice of the bounds on ATS_0 and / or $AATS$ on the cost and on the design parameters is natural issue that arises and this is presented below.

The example considered consists of a foundry operation process (Lorenzen and Vance, 1986). The carbon-silicate content of the casting is an important quality characteristic because high carbon-silicate content results in casting of low tensile strength. Periodic samples of molten iron are taken to monitor the carbon-silicate content of the casting.

In this example, the process continues in production during the search for the assignable cause ($\delta_1 = 1$), but it is stopped for repair ($\delta_2 = 0$). The average time the process stays in control is 50 hours. The sampling cost of each piece is \$ 4.22. When the process goes to an out of control condition and the assignable cause is identified, the production process is stopped and should be repaired and re-initialized; this takes about 45 minutes. The search of an assignable cause, independently, if it exists or not, take about of 5 minutes.

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The costs per hour due to non-conformities produced while the process is in control and out of control are, respectively, \$ 114.24 and \$ 949.20. The cost per false alarm is \$ 977.40 and it is equal to the cost of repairing. Then, considering the notation introduce, the input parameters are: $1/\lambda = 50$ h; $T_{**} = 45/60$ h; $T_0 = T_* = 5/60$ h; $C_0 = \$\ 114.24$/h; $C_1 = \$\ 949.20$/h; $Y = W = \$\ 977.40$: $C_{am} = a + bn$; ($a = 0$; $b = \$\ 4.22$).

To accomodate limitations of practical order, the optimization of the unit cost function was accomplished considering the following constraints: $n_1 < n_2$; $n_1 \geq 1$; $n_2 \geq 1$; $0.1 \leq h_2 < h_1$; $h_1 \geq 1$; $0.1 \leq w_2 < w_1$; $1 \leq k_2 < k_1$. A nonlinear constrained optimization algorithm available in MATLAB (MATLAB Optimization Toolbox, 1994) was applied to the cost function.

For each shift of the mean ($\delta = 0.5; 0.75$), the *ECTU* was optimized. Since the convexity of the objective function could not be ascertained, different starting vectors were used in the optimization process to find the minimum value of the *ECTU* and the corresponding optimal design parameters. For each specific shift, all searches converged to the same solution, independently of the given starting vectors, providing evidence that, probably, the global minimum was attained.

Sensitivy Analysis of the Cost and the Design Parameters to the Bounds on ATS_0 and *AATS*

For the example considered, *ECTU* was optimized subject to constraints on ATS_0 and *AATS*. The more stringent lower bound chosen for the ATS_0 was 500 hours and the more relax upper bound considered for the *AATS* was 4 hours. These values were chosen considering literature sugestions (Saniga, 1989; Prabhu et al., 1997). According to the literature, control charts which have an average rate of false alarms greater or equal than 500 hours and detect a shift in the mean of the process in an average time smaller or equal than 4 hours are considered good statistical devices for the process control. Still, according to the literature, when the goal is to detect mean shifts in the interval [0.5; 1.0] standard deviation, control charts having $AATS \leq 8$ h are still considered good statistical devices.

The following analyses were conducted:

Variation of the Upper Bound *u* on *AATS*. For the shift $\delta = 0.5$, the restriction on ATS_0 was kept fixed ($ATS_0 \geq 500$); but the upper bound u on *AATS* was allowed to vary, in order to show the behaviour of the optimal *ECTU* and the optimal design parameters when more restrictive constraints were imposed on *AATS*.

Six upper bounds (u) for the *AATS* were considered: 1.0 h, 1.5 h, 2.0 h, 2.5 h, 3.0 h, and 4.0 h. *ECTU* was minimized subject to $ATS_0 \geq 500$ and $AATS \leq u$, u taking the values considered above. Then for each restriction considered to the *AATS*, the optimal *ECTU* and design parameters were obtained. These results allowed to build the plots shown in Figure 1. The same kind of analysis was repeated for $\delta = 0.75$. Qualitatively, the same behavior described below for $\delta = 0.5$ was observed.

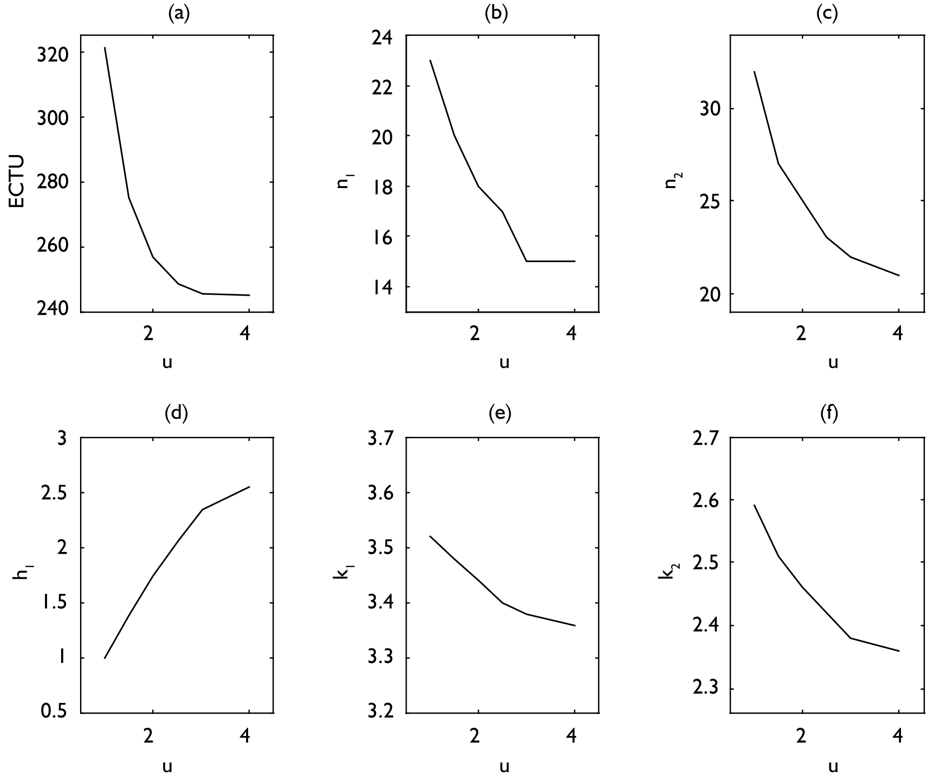

Figure 1 – Effect on the cost and the design parameters due to the bounds on *AATS*.

Variation of the Lower Bound *l* on ATS_0. For the shift $\delta = 0.5$, the restriction on *AATS* was kept fixed ($AATS \leq 4$); but the lower bound on ATS_0 was allowed to vary. Four lower bounds (l) on ATS_0 were considered: 200, 300, 400, and 500 hours. For each lower bound for the ATS_0, *ECTU* was minimized subject to $ATS0 \geq l$ and $AATS \leq 4$. Then, the optimal *ECTU* and design parameters were obtained. The results are shown in Figure 2.

Sensitivity of the Solution to the Upper Bound *u* on *AATS*

Figure 1a shows that tighter constraints on *AATS* increase the *ECTU*, or in another way, as u, the upper bound on *AATS*, increases, the cost (*ECTU*) decreases, becoming insensitive to restrictions on *AATS* from $u = 3$. Note also that the cost decrease is quite rapid around smaller values of u.

Figures 1b and 1c show, respectively, that as u increases the values of the sample sizes n_1 and n_2 decrease. However, from $u = 3$, n_1 became insensitive to restrictions on *AATS*. From Figure 1d it can be noted that as u decreases, h_1 decreases, that is, with tighter restrictions on *AATS* samples are taken more often. From $u = 3$, h_1 became less sensitive to restrictions on

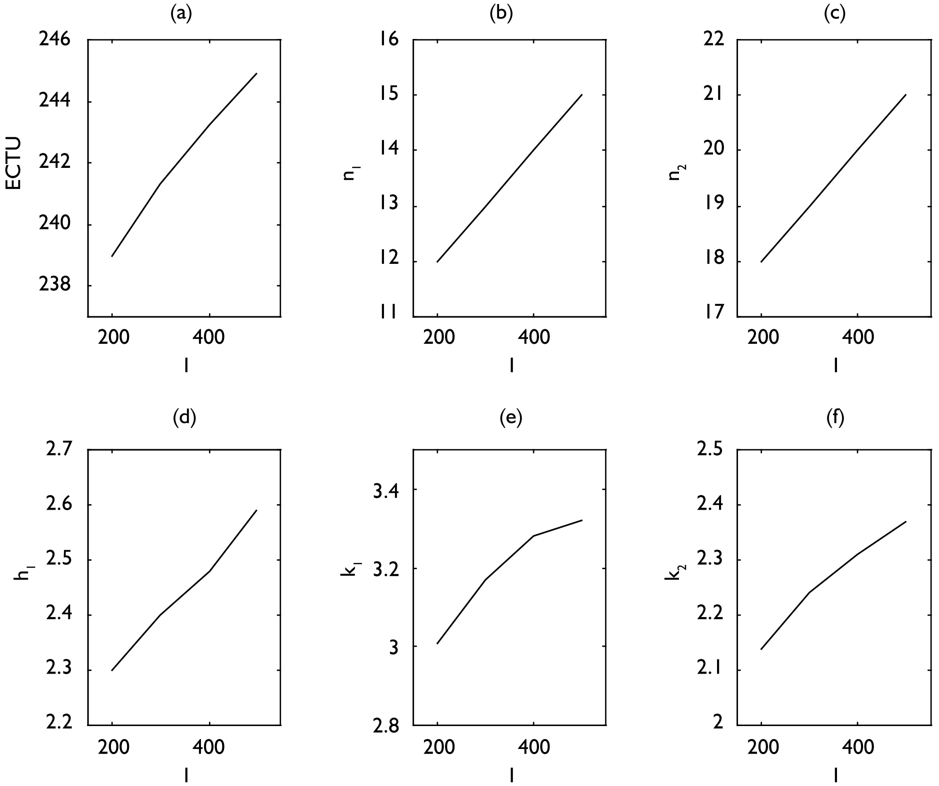

Figure 2 – Effect on the cost and the design parameters due to the bounds on ATS_0.

$AATS$. The sampling interval h_2 is insensitive to constraints on $AATS$, it assumes always the value 0.1. Figures 1e and 1f show that as u increases, k_1 and k_2 decrease. In fact, when u varies from 1 hour to 4 hours, k_1 decreases from 3.52 to 3.36, and k_2 decreases from 2.58 to 2.36.

As said before, the same kind of analysis was repeated for $\delta = 0.75$ and, qualitatively, the same behavior described for $\delta = 0.5$ was observed. However, it should be mentioned that for each shift (for the shifts considered, $\delta = 0.5$ e $\delta = 0.75$), there is a value, say u^*, for the bound of $AATS$ such that for any value u of the bound above u^*, the $ECTU$ does not change. This is due to the fact that for bounds above u^*, the optimal values of $ECTU$ have $AATS$ strictly less than the bound. The value of u^* decreases when δ increases.

Sensitivity of the Solution to the Lower Bound l on ATS_0

Figures 2a and 2d show, respectively, that restrictions on ATS_0 produce an approximately linear and increasing effect on the cost and the sampling interval h_1. Figures 2b and 2c show that restrictions on ATS_0 produce a linear increasing effect on the sample sizes n_1 and n_2.

The sampling interval h_2 is insensitive to restrictions on ATS_0. As before, it assumes always the value 0.1. Figures 2e and 2f show that wider restrictions on ATS_0 make k_1 and k_2 values decrease.

Conclusions

The main goal of an economic-statistical model for control charts is to improve the statistical performance of economic models. Considering the economic-statistical model for VP $\bar{X}$ control charts developed by De Magalhães et al. (2002), in which constraints are imposed on the average times until a signal (ATS_0 and $AATS$), an analysis of the effect of the choice of these bounds on the optimal design parameters and cost was performed. To have an idea of how the design parameters and the expected cost per time unit vary is an important decision factor. In fact, since the bounds on the $AATS$ and on ATS_0 are to a certain extent arbitrary, so if they lead to a large expected cost, the user may try to vary one or both of these bounds to diminish the cost.

To make the paper more relevant to practitioners the following observations are worthy of notice. Once we are working with an economic-statistical model for a VP $\bar{X}$ chart, finding the design parameters is not trivial; however, the results provide some guidelines as how to set control limits, sampling intervals and sample sizes according to the bounds on the $AATS$ and ATS_0 that one is willing to have in a process.

For the process considered, when the process is out of control ($\delta = 0.5$) and if it is desirable to detect this condition in less than 2 hours, then, from the analysis provided, the ranges of the design parameters should be: $18 \le n_1 \le 24$, $25 \le n_2 \le 35$, $1 < h_1 < 2$, $3.42 < k_1 < 3.52$, $2.46 < k_2 < 2.58$, considering an average rate of false alarms greater than or equal to 500 hours ($ATS_0 \ge 500$ hours). For these ranges of design parameters the $ECTU$ varies between 258 dollars to 320 dollars.

Generalizations based on the results will probably provide more insight to practitioners. For example, the results show that the small sample size (n_1) never falls below 14 (when the bounds on $AATS$ are varying) and never falls below 12 (when the bounds on ATS_0 are varying) for the case studied in this article.

As said before, the primary reason to develop adaptive control charts is to improve the efficiency of the traditional (Shewhart) control charts in the detection of small to moderate shifts of the target value (0.5 σ to 1.5 σ). Therefore, we made a sensitivity analysis for $\delta = 0.5$ to check the performance of the VP $\bar{X}$ chart in the presence of a small shift. The same kind of analysis was repeated for $\delta = 0.75$ and, qualitatively, the results are similar to the ones obtained for $\delta = 0.5$. From this, we surmise that similar qualitative behavior holds for other values of δ.

In this way, even though the article has worked with a specific example, the study provides a useful insight to quality control designers in making the trade-off decision between the expected cost and desired levels of statistical properties.

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Using Geostatistics to Estimate the Variability of Autocorrelated Processes

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Abstract

Statistical quality control is used to detect changes in the parameters values of the process which usually are estimated under the assumption of independence of the sampling units with respect to the quality characteristic. However, this is questionable for many processes. The main objective of this paper is to present estimators for the variance of autocorrelated processes by using Geostatistics methodology. With this new procedure the usual Shewhart's control charts still can be used to monitor the quality of the process. A Monte Carlo simulation study showed that the proposed estimators have good performance.

Keywords: variability, autocorrelation, geostatistics, semivariogram, shewhart's control charts

Introduction

The quality of a process is usually monitored by control charts. Basically, they are a representation of the quality characteristic measured in a sample or in several samples of the process. These charts define an area where the values of the quality characteristic (X), or its average, should stay for the process to be considered under control. For continuous inspection the chart for average contains a central line (CL) that represents the average value of the quality characteristic and two horizontal lines called lower and upper control limits (LCL; UCL) calculated under the assumption that X has a normal distribution. Sample points outside the limits are an indication that the process is "out of control" (Montgomery, 2001). As a consequence, there is always a probability of rejecting the "under control condition" of the process erroneously, which is defined as "false alarm". This is the case where the sample points, or averages, fall outside the control limits due to

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the randomness of the normal distribution and not due the fact that some modification of the process parameters had occurred. Under the normality assumption the control limits for the average of the process are given by the following equations:

$$UCL = \mu + k\frac{\sigma}{\sqrt{n}};\ CL = \mu;\ LCL = \mu - k\frac{\sigma}{\sqrt{n}} \tag{1}$$

where μ and σ are the average and the standard deviation of X, respectively and k is the distance of the control limits to the central line expressed in units of standard deviation.

In practice the values of μ and σ are estimated from samples of the process, when it is just under the effect of "common" or "random" causes. Let $X_1, X_2, \ldots, X_n$ be the observed values of a random sample of the process. Then the parameter μ is estimated by the sample mean $\overline{X}$ and the parameter σ is estimated by the standard deviation (s) or the moving sample range ($\hat{\sigma}_{AM}$) defined respectively as

$$s = \left[\frac{1}{n-1}\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2\right]^{1/2} \quad \text{where} \quad \overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{2}$$

$$\hat{\sigma}_{AM} = \frac{\overline{AM}}{1.128},\ \text{where}\ \overline{AM} = \frac{\sum_{i=2}^{n} AM_i}{n-1}\ \text{and}\ AM_i = |X_i - X_{i-1}| \tag{3}$$

The variance of the process (σ^2) is estimated by the square of the estimators (2) and (3), respectively.

These classical estimation procedures are based on the assumption of independence among the sample units of the process with respect to the quality characteristic X being measured. As mentioned in Alwan and Roberts (1995) this assumption is very questionable especially for chemical processes (Zhang, 1998). With the advances of the technology, processes can be sampled at higher rates which often leads to autocorrelated data. When the estimators (2) or (3) are used to estimate the standard deviaton σ of an autocorrelated process then the chance of "false alarms" or not detecting the "out of control" condition may increase because the calculated control limits will be shorter or wider than the true limits of the process. According to Zhang (1998) and Box and Luceno (1997) positive correlation occurs more frequently in practical situations.

A decrease in the correlation effect can be achieved by increasing sampling units interval. However, this alternative can increase the time needed to detect that the process is "out of control" and for some continuous processes of production it can not be implemented. Corrections of control limits when the correlation is intrinsically part of the process are being proposed in the literature by several authors using time series models (Alwan and Roberts, 1989; Runger and Willemain, 1995). One of these alternatives is the identification and adjustment of the ARIMA model (Box and Jenkins, 1976) for the series of the process observations. After the adjustment, the residuals of the model are obtained and Shewhart's control charts are constructed to the series of residuals, which by assumption should be independent and identically distributed according to a normal distribution. The possible changes that could happen in the average of the process would be reflected in the behavior of the residuals (Box and Luceno, 1997). Although very interesting, this alternative demands the right identification of the ARIMA model and the calculation of the residual for each new collected sample. Another alternative is to monitor the process by using the *EWMA* (Exponentially Weighted Moving Average) charts proposed iniatially by Roberts (1959) and discussed by Montgomery and Mastrangelo (1991), Hunter (1998, 1986) among others. Basically the statistical *EWMA* model is defined as

$$Z_t = \lambda X_t + (1 - \lambda) Z_{t-1} \quad (4)$$

where $0 \leq \lambda \leq 1$ is a constant which needs to be determined by the user and X_t is the value of the quality characteristic X observed for the sample t, $t = 1,2,\ldots,n$. By using the model (4) the series of the one step forecasts errors is obtained and Shewhart's control charts are then applied to the series of errors which theoretically should be uncorrelated. The choice of the constant λ in (4) is discussed in Crowder (1989), Lucas and Saccucci (1990), Box and Luceno (1997) among others. Basically, it is chosen to minimize the sum of squares of the one step forecasts prediction errors. Hunter (1998) claimed that the *EWMA* control chart is simpler to implement and can be an efficient tool to be used in companies daily routine. Another approach proposed by Krieger, Champ and Alwan (1992) and Alwan and Alwan (1994) is to use multivariate control such as Hotelling's T^2 chart or multivariate CUSUM chart to treat observations of an autocorrelated univariate process. This is done by forming a multivariate vector of a moving window of observations from the process. In this approach it is necessary to choose the time delay between samples in such way that the constructed vectors are almost uncorrelated. Apley and Tsung (2002) modified this idea allowing correlation between samples.

The main purpose of this paper is to introduce an automatic and simpler form to monitor the process in the presence of correlation. The alternative we will propose does not depend upon the identification and adjustment of ARIMA models as well as the calculation of one step prediction errors. The idea is to use Geostatistics methodology (Cressie, 1993) to estimate the variance and the standard deviation of the process. The quality of the process is then monitored by the usual Shewhart's charts applied to original characteristic X of interest by replacing the classical standard deviation estimator in the Shewhart' control charts for a geostatistical estimator of σ. The correction of the charts due to presence of the correlation is automatically incorporated in the control limits UCL and LCL. The results of a simulation study comparing the geostatistical with the classical estimators will be presented.

Discussing the Effects of the Correlation: ARIMA Models

In the context of the ARIMA models it is interesting to observe that the correlation effect in the estimator s^2 is more accentuated in situations where the observations are generated by an auto regressive process (AR) where s^2 is the square of s in (2). To see this consider the AR(1) and MA(1) models defined as

$$X_t = \phi X_{t-1} + a_t + \delta \quad (5)$$

$$X_t = a_t - \theta a_{t-1} + \mu \quad (6)$$

where $|\phi| < 1$, $|\theta| < 1$, δ and μ are constants and $a_t \sim N(0, \sigma^2_a)$ is a white noise series. In the AR(1) and MA(1) models the first order autocorrelation is given by $\phi = \rho_1$ and $\rho_1 = \frac{-\theta}{1+\theta^2}$, respectively.

Zhang (1998) had shown that the expectation of the estimator s^2 for an autocorrelated process is given by

$$E\left[s^2\right] = \sigma^2\left[1 - \frac{2}{n(n-1)}\sum_{h=1}^{n-1}(n-h)\rho_h\right] \quad (7)$$

where $\rho_h = Corr(X_i, X_{i+h})$. As we can see from (7) if $\rho_h > 0$, $\forall h$, then $E[s^2]$ will be smaller than the true value s^2. If $\rho_h < 0$, $\forall h$, then $E[s^2]$ will be larger than σ^2. For processes with a mixture of positive and negative correlation $E[s^2]$ could be smalller or larger than the true value of σ^2 and for large sample sizes (7) converges to σ^2. For the AR(1) and MA(1) the expression (7) reduces respectively to:

$$E\left[s^2\right] = \sigma^2\left[1 - \frac{2}{n(n-1)}\phi\left(\frac{n - n\phi - 1 + \phi^n}{(1-\phi)^2}\right)\right] = C(n,\phi)\sigma^2 \quad (8)$$

$$E\left[s^2\right] = \sigma^2\left[1 + \frac{2\theta}{n(1+\theta^2)}\right] = C(n,\theta)\sigma^2 \quad (9)$$

Tables 1 and 2 show the values of $C(n, \phi)$ and $C(n, \theta)$ for samples of sizes $n = 25, 100$, $\phi \in [-0.9, 0.9]$ and $\theta \in [-0.9, 0.9]$. It can be seen that for AR(1) the bias of s^2 is higher for $n = 25$ and positive high correlation. For MA(1) model the bias is negligible for both sample sizes and for all values of θ.

Geostatistics Methodology

The Geostatistics methodology was initially formulated with the purpose to analyse geological data (Matheron, 1963). Nowdays, it has been used in many other fields. Several examples appear in the study of pluviometric precipitation or atmospheric data (Ord and Rees, 1979; Thiebaux and Pedder, 1987; Kitanidis,1997), or in study of ground water-flow (Cressie, 1993; Yeh et al.,1995). Geostatistics has also been applied for variables that are not of physical-chemistry nature such as rates of infantile mortality and abundance of species (Cressie, 1993). In quality control, applications of Geostatistics can be found in mining industry and in sampling of materials of continuous flow (Gy, 1998, 1982). Some

Table 1 – Values of C(n, ϕ) - AR(1).

ϕ	$n = 25$	$n = 100$
0.90	0.53	0.84
0.80	0.73	0.92
0.70	0.83	0.95
0.60	0.89	0.97
0.50	0.92	0.98
0.40	0.95	0.99
0.30	0.97	0.99
0.20	0.98	1.00
0.10	0.99	1.00
0.00	1.00	1.00
- 0.10	1.01	1.00
- 0.20	1.01	1.00
- 0.30	1.02	1.00
- 0.40	1.02	1.01
- 0.50	1.03	1.01
- 0.60	1.03	1.01
- 0.70	1.03	1.01
- 0.80	1.04	1.01
- 0.90	1.04	1.01

Table 2 – Values of $C(n, \phi)$ - MA(1).

θ	ρ_1	$n = 25$	$n = 100$
0.90	- 0.50	1.04	1.01
0.80	- 0.49	1.04	1.01
0.70	- 0.47	1.04	1.01
0.60	- 0.44	1.04	1.01
0.50	- 0.40	1.03	1.01
0.40	- 0.34	1.03	1.01
0.30	- 0.28	1.02	1.01
0.20	- 0.19	1.02	1.00
0.10	- 0.10	1.01	1.00
0.00	0.00	1.00	1.00
- 0.10	0.10	0.99	1.00
- 0.20	0.19	0.98	1.00
- 0.30	0.28	0.98	0.99
- 0.40	0.34	0.97	0.99
- 0.50	0.40	0.97	0.99
- 0.60	0.44	0.96	0.99
- 0.70	0.47	0.96	0.99
- 0.80	0.49	0.96	0.99
- 0.90	0.50	0.96	0.99

general references in Geostatistics are Cressie (1993), Journell and Huijbregts (1997), Chilès and Delfiner (1999) and Houlding (2000).

Briefly speaking, suppose we have a random sample of a random variable X collected in many different locations from a certain area. In this case, statistical models are build with the main objective to predict the value of X for locations not in the original sample. These models incorporate the information of the existing relationship among the sample values of X for different locations through a function called semivariogram (or variogram) which plays an important role in the spatial prediction procedure called Kriging (Cressie, 1993). In the Kriging procedure the value of X for a new location with coordinates s_0 for example, is predicted based upon the values of X in a neighborhood of s_0. Although Geostatistics can be used for locations in $\Re^d$ space most of the applications are related to $\Re^2$. Next we will introduce the Geostatistics definitions in $\Re$ space.

Geostatistics in the $\Re$ *Domain: Main Concepts*

The sequence of observed values of the quality characteristic X can be treated as a trajectory of a stochastic process $\{X(t), t \in \Re\}$.The variability of the process can be expressed in terms of the theoretical semivariogram of the process. Two assumptions are necessary: intrinsically stationarity and the isotropy. Shortly, these assumptions are described as follows:

A. Intrinsically Stationarity: The stochastic process $\{X(t), t \in \Re\}$ is such that:

$(i)\ E[X(t)] = \mu, \forall t \in \Re$;

$(ii)\ \text{Var}[X(t_l) - X(t_k)] = 2\gamma(\|t_l - t_k\|), \forall t_l \neq t_k, \in \Re$,

which means that the process has constant average in $\Re$, and for all $t_l, t_k \in \Re$, $t_l \neq t_k$, the variance of the difference $[X(t_l) - X(t_k)]$ is a function only of the difference $\|t_l - t_k\|$ depending on its magnitude and direction. The funcions $2\gamma(\bullet)$ and $\gamma(\bullet)$ are called variogram and semivariogram of the process, respectively.

B. Isotropy: If the variogram $2\gamma(\bullet)$ is a function only of the distance among the sample units then the process is said to be isotropic.

In the case of industrial processes, condition i) is equivalent to say that the process is "under control" in relation to the average and condition ii) indicates that the variability of the difference between any two observations of the process is just a function of the distance between them. The isotropy means that the future and the past of the process are described by the same variogram function. In practice, the intrinsically stationarity and isotropy are reasonable assumptions for the industrial processes when they are in the "under control" condition. The $\Re$ space covers situations where samples were collected on time domain as well situations where samples were collected in some specific order not necessarily time. Therefore, each sample has its own "reference location" in the space and Geostatistics can be applied to analyse the data. Theoretically, it is expected that the correlation between any two sample units of the process decreases to zero as the distance between them increases. Therefore, after a certain point c the natural variability is the only source affecting the process. Some common semivariograms models are: spherical, linear, gaussian, exponential and wave (Cressie, 1993). In practice the theoretical semivariogram is estimated by using a sample of the process $\{X(t), t \in \Re\}$.

At this point it is interesting to notice that for intrinsically stationarity and isotropic processes the semivariogram $\gamma(\bullet)$ can be expressed as

$$\gamma(h) = 1/2\{Var[X(t+h) - X(t)]\} = 1/2\{Var[X(t+h)] + Var[X(t)]\} - Cov[X(t), X(t+h)] = \sigma^2 - \sigma^2\, Corr[X(t), X(t+h)] = \sigma^2(1 - \rho_h),\ \forall\, h \quad (10)$$

where ρ_h is the correlation between X_i and X_j, $|i-j| = h$, $i \neq j$.When the correlation is equal to zero the semivariogram of order h is equal to the natural variance σ^2 of the process. By the Eq. (10) it is clear that in order to estimate the variance σ^2 it will be enough to have estimators of the semivariogram $\gamma(\bullet)$ and the correlation of order h, ρ_h. Therefore, it is possible to create many alternative estimators for the variance σ^2 that automatically will take into account the correlation of the process. There are many semivariogram estimators for $\gamma(h)$, called experimental semivariograms (Cressie, 1993) but Matheron's (1963) classic estimator is the most well known. Given a sample of n observations of the process, denoted by $X_1, X_2, \ldots, X_n$, Matheron's estimator of $\gamma(h)$ is defined as

$$\hat{\gamma}(h) = \frac{1}{2}\,\frac{\sum_{i=1}^{n-h}\left[X_i - X_{i+h}\right]^2}{n-h}, \quad \forall\, h \in T \quad (11)$$

where X_i is the value of the quality characteristic X for the sample unit i, $i = 1, 2, \ldots, n$, $T = \{1, 2, \ldots, n-1\}$, $(n-h)$ is the number of pairs (X_i, X_j) such that $|i-j| = h$, $i \neq j$. The autocorrelation function of order h, ρ_h, is estimated by

$$\hat{\rho}_h = \frac{\sum_{i=1}^{n-h}\left(X_i - \overline{X}\right)\left(X_{i+h} - \overline{X}\right)}{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2} \quad (12)$$

where $\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$ is the sample mean. The functions $(\gamma(h), \rho_h)$ are estimated under the assumption that the process is intrinsically stationary and isotropic which is the same as saying that the process is "under control". In the next section we present the new estimators for σ^2 that will be discussed in this paper.

New Estimators for the Process Variability: Geostatistics Approach

In Mingoti (2000) and Neves (2001) several estimators were proposed to estimate the variance σ^2 of autocorrelated processes based on Geostatistics methodology. In this paper we will present a comparison of the geoestatistical estimators with the classical estimators (2) and (3). They were constructed considering the relation (10) of section 3. All geostatistical estimators are biased but the bias converges to zero for large samples. In all cases an estimate of the standard deviation is obtained by taking the square root of the estimated variance.

The estimator $\hat{\sigma}^2_1$ defined as

$$\hat{\sigma}^2_1 = \frac{\hat{\gamma}_1}{1-\hat{\rho}_1} \tag{13}$$

takes into account only the semivariogram and autocorrelation of order 1 and it is very simple to calculate. The estimator $\hat{\sigma}^2_2$ defined as

$$\hat{\sigma}^2_2 = \frac{\sum_{h=1}^{3} \frac{\hat{\gamma}_h}{3}}{1-\sum_{h=1}^{3} \frac{\hat{\rho}_h}{3}} \tag{14}$$

takes into account the three first semivariogram and autocorrelation values. It is an option for process which have significant correlations of order higher than 1. The estimator $\hat{\sigma}^2_3$ introduced by Mingoti and Fidelis (2001) is the average of the M semivariogram values, where M is a constant in the set $\{1,2,\ldots,(n-1)\}$. In practice M should be chosen in the neigboorhood of [n/2], where [x] denotes the larger integer number less or equal to x, and such that the number of pairs (X_i, X_j) used to estimate $\gamma(h)$ is higher ou equal to 30. This is the region where the semivariogram is estimated with better precision (Journel and Huijbregts, 1997).

$$\hat{\sigma}^2_3 = \frac{1}{M} \sum_{h=1}^{M} \hat{\gamma}_h \tag{15}$$

The estimator $\hat{\sigma}^2_4$ is an extension of the estimator $\hat{\sigma}^2_3$ and the correction term in the denominator has the purpose to decrease the bias of the estimator $\hat{\sigma}^2_3$.

$$\hat{\sigma}^2_4 = \frac{\sum_{h=1}^{M} \hat{\gamma}_h}{\sum_{h=1}^{M} (1-\hat{\rho}_h)} \tag{16}$$

Finally, the estimator $\hat{\sigma}^2_5$ is a modification of $\hat{\sigma}^2_4$ where M is defined as in $\hat{\sigma}^2_3$. The purpose of using more than just 3 semivariogram values to estimate σ^2 is to increase the precision.

$$\hat{\sigma}^2_5 = \frac{1}{M} \sum_{h=1}^{M} \frac{\hat{\gamma}_h}{(1-\hat{\rho}_h)} \tag{17}$$

The nice thing about the geostatistical estimators defined in this section is that there is no need to recognize and adjust a statistical model to the sample series of the process or to the experimental process variogram something that would be necessary if one would decide to use the "best linear unbiased estimator" obtained by using Kriging technique. Usually in $\Re$ space the experimental variogram takes to a wave form and the estimation of its parameters is not very simple (see Mingoti and Neves, 1999 for details).

The geostatistical estimators can also be used in situations where the process is monitored by using averages of rational groups. If $\overline{X}_1, \overline{X}_2, ..., \overline{X}_m$ represent the average values of m sample groups then formulas (11) and (12) should be applied to the $\overline{X}_k$ values, $k = 1, 2, ..., m$, to estimate the semivariogram and correlation of order h of the theoretical stochastic process which is generating the $\overline{X}_k$ average values. The new formulas are defined as

$$\hat{\bar{\gamma}}(h) = \frac{1}{2} \frac{\sum_{i=1}^{m-h} \left[\overline{X}_i - \overline{X}_{i+h}\right]^2}{m-h}, \forall\, h \in T^* \quad (18)$$

$$\hat{\bar{\rho}}_h = \frac{\sum_{i=1}^{m-h} \left(\overline{X}_i - \overline{\overline{X}}\right)\left(\overline{X}_{i+h} - \overline{\overline{X}}\right)}{\sum_{i=1}^{n} \left(\overline{X}_i - \overline{\overline{X}}\right)^2} \quad (19)$$

where $\overline{\overline{X}} = \frac{1}{m} \sum_{i=1}^{m} \overline{X}_i$ is the global mean, $T^* = \{1, 2, ..., m - 1\}$, and $(m - h)$ is the number of pairs $(\overline{X}_i, \overline{X}_j)$ such that $|i - j| = h$, $i \neq j$. The Shewhart's control limits for the average of the process are then given by

$$UCL = \overline{\overline{X}} + k\hat{\sigma}_i;\ CL = \overline{\overline{X}};\ LCL = \overline{\overline{X}} - k\hat{\sigma}_i \quad (20)$$

where $\hat{\sigma}_i$, is any geostatistical estimator presented in this section calculated with the semivariogram and correlation estimates given by Eqs. (18) and (19), $i = 1, 2, 3, 4, 5$.

Simulation Results

In this section we present the results of a Monte Carlo simulation study performed to evaluate the geostatistical estimators presented in section 4 for the standard deviation of the process. They were also compared to the classical estimator s and the moving sample range $\hat{\sigma}_{AM}$ defined in section 1. Samples with sizes $n = 25$, 50 and 100 were generated from an AR(1) with parameter $\phi \in [-0.9, 0.9]$ and from an ARMA(1,1) with the parameters (ϕ, θ) chosen such that $\rho_1 \in [-0.95, 0.95]$. The region of simulation contains models with long and short, positive and negative, correlation structure. As an illustration, for the AR(1) with $\phi = 0.9$ the autocorrelation for $h = 7$ is equal to 0.478 while for the AR(1) with $\phi = 0.7$ the autocorrelation for $h = 3$ is only 0.34. The choice of AR(1) and ARMA(1,1) was due to the fact that those are the more commom models for autocorrelated processes according to the literature (see Box and Luceno, 1997; Zhang, 1998). All generated processes had the same fixed mean. The white noise was generated from a normal distribution with zero mean and standard deviation σ_a ranging from 2 to 7. The constant $M = [n / 2]$ was used for the geostatistical estimators when needed. A total of $r = 100$ samples were generated for each case and the Mean Error (*ME*), the Mean Absolute Error (*MAE*) and the Mean Square Error (*MSE*), were calculated for all the estimators. The average results for the AR(1) and ARMA (1,1) considering all simulated cases, are shown in Tables 3 and 4 as a function of the true correlation ρ_1. The respective values of (ϕ, θ) are also shown in the Table 4. Table 5 presents the average results as a function of the white noise standard deviation σ_a. From Tables 3 and 4 it can be seen that in the presence of correlation the geostatistical estimators had better or similar performance than the classical estimators s and $\hat{\sigma}_{AM}$. Among the geostatistical estimators in general, for high negative correlation the estimator $\hat{\sigma}_5$ had a better performance; for intermediate negative correlation $\hat{\sigma}_1$ and $\hat{\sigma}_2$ had smaller error values (*ME, MAE, MSE*) and for high positive correlation the estimators $\hat{\sigma}_1$ and $\hat{\sigma}_2$ had a better performance. When the correlation is small the average errors of all the estimators are more similar. For high positive correlation the estimator $\hat{\sigma}_3$ presented smaller errors than the classical estimators. Considering that the estimator $\hat{\sigma}_3$ does not have any correcting factor for bias this is an interesting result. In general the estimator $\hat{\sigma}_4$ presented larger errors than the estimator s but the difference was not very accentuated. In all cases the moving sample range estimator $\hat{\sigma}_{AM}$ had a very bad performance with larger error values especially the *MSE*. From Table 5 it can be seen that for all the estimators the error values increase as σ_a increases. The increase rate is much higher for the ARMA than the AR process. The geostatistical estimator $\hat{\sigma}_5$ had superior performance for the ARMA process and a good performance for the AR. Table 6 presents the average results as a function of the sample size n. As expected for all the estimators the errors decrease as n increases. In general the errors (*ME, MAE, MSE*) are larger for ARMA than for AR process. The *MSE* values for the $\hat{\sigma}_{AM}$ are intolerable for small and larger sample sizes. By considering the average results *ME, MAE, MSE* for all cases presented in Tables 3 and 4 for AR(1) and ARMA(1,1) we can see that the classical standard sample deviation had smaller values only in 2 cases for AR(1) and in 4 cases for ARMA(1,1) compared to the geostatistical estimators.

Example of Application

Table 7 presents the observed values of waiting time in line (in minutes) for 40 customers of a laboratory. The autocorrelation and semivariogram estimates for $h = 1, 2, \ldots, 20$, are presented in Table 8. Table 9 shows the obtained estimates for the standard deviation σ using all 7 estimators discussed in this paper. As an example, Shewhart's control charts for the average waiting time using the sample standard deviation s and the geostatistical estimator $\hat{\sigma}_1$ are presented in Figure 1. As one can see the control limits calculated by using the estimator $\hat{\sigma}_1$ are shorter than the limits calculated using the sample standard deviation. The moving range estimate was the smallest value and completelly different from all the others 6 estimators (see Table 9).

Table 3 – Average results for the geostatistical and classical estimators of the standard deviation of the process - AR(1).

$\lvert\rho_1\rvert$		$\rho_1 > 0$			$\rho_1 < 0$		
	$\hat{\sigma}_i$	*ME*	*MAE*	*MSE*	*ME*	*MAE*	*MSE*
	1	- 0.4243	1.0335	1.9583	0.5342	1.1923	3.0837
	2	- 0.3809	1.0602	2.0534	0.5670	1.1920	3.0572
	3	- 0.0031	1.2224	2.8055	0.6467	1.2462	3.2508
0.90	4	0.4943	1.2181	2.9182	0.5268	1.1978	2.9763
	5	0.2564	1.1317	2.4271	0.2600	1.1031	2.3821
	6	- 7.2270	7.2270	59.7367	5.3278	5.3344	40.3307
	7	0.4480	1.2065	2.8856	0.5719	1.2141	3.2336
	1	- 0.2413	0.7720	1.1740	0.2077	0.8351	1.4732
	2	- 0.2185	0.7871	1.2068	0.2201	0.8325	1.4526
	3	0.0899	0.9275	1.6343	0.2881	0.8836	1.6062
0.85	4	0.3130	0.8935	1.5355	0.1893	0.8570	1.4949
	5	0.1798	0.8500	1.3690	0.0549	0.8345	1.3871
	6	- 5.2959	5.2959	32.2813	3.7714	3.7858	19.8403
	7	0.2457	0.8516	1.4333	0.2415	0.8503	1.5427
	1	- 0.2010	0.6825	0.8956	0.0958	0.6773	0.8712
	2	- 0.1619	0.6797	0.9050	0.0960	0.6727	0.8605
	3	0.0703	0.7961	1.2115	0.1511	0.7020	0.9484
0.80	4	0.1812	0.7422	1.0662	0.0646	0.6847	0.8909
	5	0.0982	0.7189	0.9950	- 0.0219	0.6808	0.8742
	6	- 4.2090	4.2090	20.4759	2.9620	2.9677	12.0537
	7	0.2149	0.9275	1.5323	0.2269	0.9271	1.5205
	1	- 0.1799	0.6220	0.7267	0.0318	0.5992	0.7082
	2	- 0.1431	0.6285	0.7530	0.0268	0.5989	0.7045
	3	0.0581	0.6992	0.9559	0.0847	0.6213	0.7661
0.75	4	0.1092	0.6598	0.8585	0.0075	0.6093	0.7355
	5	0.0480	0.6456	0.8118	- 0.0530	0.6069	0.7315
	6	- 3.4686	3.4686	13.9468	2.4578	2.4793	8.5000
	7	0.0695	0.6277	0.7727	0.0649	0.6064	0.7284
	1	- 0.1604	0.5613	0.6068	0.0069	0.5528	0.5689
	2	- 0.1314	0.5676	0.6139	- 0.0022	0.5513	0.5638
	3	0.0195	0.6216	0.7572	0.0585	0.5734	0.6147
0.70	4	0.0521	0.5877	0.6726	- 0.0127	0.5656	0.5978
	5	0.0066	0.5803	0.6491	- 0.0584	0.5659	0.5989
	6	- 2.9176	2.9176	9.9615	2.0835	2.1026	6.1243
	7	0.0444	0.5645	0.6294	0.0412	0.5590	0.5847
	1	- 0.1536	0.4936	0.4826	- 0.0161	0.4821	0.4682
	2	- 0.1241	0.4918	0.4807	- 0.0290	0.4831	0.4719
	3	- 0.0074	0.5239	0.5592	0.0282	0.5026	0.5105
0.60	4	- 0.0109	0.4990	0.4994	- 0.0332	0.4969	0.4953
	5	- 0.0399	0.4972	0.4931	- 0.0631	0.4984	0.4972
	6	- 2.1700	2.1700	5.5370	1.5931	1.6205	3.8033
	7	- 0.0100	0.4831	0.4669	0.0195	0.4871	0.4766
	1	- 0.1540	0.4533	0.3955	- 0.0533	0.4318	0.3618
	2	- 0.1301	0.4529	0.3933	- 0.0670	0.4340	0.3640
	3	- 0.0416	0.4660	0.4170	- 0.0141	0.4480	0.3868
0.50	4	- 0.0605	0.4539	0.3929	- 0.0695	0.4461	0.3812
	5	- 0.0825	0.4540	0.3922	- 0.0920	0.4479	0.3831
	6	- 1.6044	1.6047	3.1773	1.1886	1.2228	2.2513
	7	0.0069	0.4857	0.4554	0.0214	0.4877	0.4586
	1	- 0.0823	0.4021	0.3111	- 0.0563	0.4130	0.3420
	2	- 0.0660	0.4011	0.3073	- 0.0651	0.4137	0.3425
	3	- 0.0024	0.4054	0.3142	- 0.0143	0.4222	0.3527
0.30	4	- 0.0343	0.4024	0.3086	- 0.0613	0.4195	0.3510
	5	- 0.0490	0.4027	0.3081	- 0.0757	0.4199	0.3526
	6	- 0.8069	0.8303	0.9973	0.6464	0.7580	0.9911
	7	- 0.0024	0.3974	0.3032	- 0.0141	0.4156	0.3456

(*) $\hat{\sigma}_6 = \hat{\sigma}_{AM}$ is the classical moving range estimator;
$\hat{\sigma}_7 = s$ is the classical standard sample deviation.

Table 4 – Average results for the geostatistical and classical estimators of the standard deviation of the process - ARMA(1,1).

	(ρ_1, ϕ, θ)											
	(- 0.95, - 0.9, 0.9)			(- 0.88, - 0.9, - 0.1)			(- 0.71, - 0.5, 0.5)			(- 0.64, - 0.7, - 0.1)		
$\hat{\sigma}_i$	*ME*	*MAE*	*MSE*	*ME*	*MAE*	*MSE*	*ME*	*MAE*	*MSE*	*ME*	*MAE*	*MSE*
1	1.7894	3.2760	23.0016	0.4372	1.0220	2.1037	- 0.0746	0.5112	0.4993	- 0.0987	0.4085	0.3195
2	1.9032	3.3174	23.5941	0.4613	1.0242	2.0877	- 0.0850	0.5123	0.4980	- 0.1085	0.4097	0.3202
3	2.0993	3.4337	25.0951	0.5513	1.0969	2.3307	- 0.0410	0.5222	0.5161	- 0.0626	0.4127	0.3257
4	1.8692	3.3286	23.4263	0.4424	1.0540	2.1274	- 0.1049	0.5236	0.5166	- 0.1060	0.4157	0.3284
5	1.2222	3.0179	17.8430	0.2196	0.9780	1.7826	- 0.1413	0.5282	0.5252	- 0.1203	0.4176	0.3303
6	11.5237	11.5452	203.9942	4.7097	4.7179	30.7231	1.7022	1.7260	4.3521	0.4791	0.6207	0.7237
7	1.8379	3.3047	23.5058	0.4738	1.0413	2.2114	- 0.0404	0.5130	0.5064	- 0.0518	0.4059	0.3180
	(ρ_1, ϕ, θ)											
	(- 0.47, - 0.1, 0.5)			(- 0.24, - 0.7, - 0.5)			(0.95, 0.9, - 0.9)			(0.88, 0.9, 0.1)		
$\hat{\sigma}_i$	*ME*	*MAE*	*MSE*	*ME*	*MAE*	*MSE*	*ME*	*MAE*	*MSE*	*ME*	*MAE*	*MSE*
1	0.0545	0.6276	0.7691	0.0028	0.4633	0.4202	- 0.5683	1.4507	5.4771	- 0.3584	0.9148	1.5531
2	0.0386	0.6293	0.7717	- 0.0109	0.4647	0.4233	- 0.5293	2.4852	10.8687	- 0.3661	0.9266	1.6054
3	0.1040	0.6611	0.8750	0.0426	0.4803	0.4502	0.0894	2.7353	13.6426	0.0107	1.0844	2.1658
4	0.0237	0.6483	0.8293	- 0.0160	0.4746	0.4340	1.1699	2.8752	16.1518	0.4046	1.0514	2.0852
5	- 0.0196	0.6466	0.8209	- 0.0373	0.4749	0.4331	0.6720	2.6774	13.5529	0.2025	0.9723	1.7746
6	2.3295	2.3449	7.7694	1.2061	1.2420	2.3625	- 14.7894	14.7894	250.7075	- 6.2217	6.2217	44.4910
7	0.0894	0.6351	0.7888	0.0428	0.4682	0.4286	1.0407	2.8365	15.9467	0.3543	1.0177	2.0021
	(ρ_1, ϕ, θ)											
	(0.71, 0.5, - 0.5)			(0.64, 0.7, 0.1)			(0.47, 0.1, - 0.5)			(0.24, 0.7, 0.5)		
$\hat{\sigma}_i$	*ME*	*MAE*	*MSE*	*ME*	*MAE*	*MSE*	*ME*	*MAE*	*MSE*	*ME*	*MAE*	*MSE*
1	- 0.1944	0.5284	0.5304	- 0.1093	0.5729	0.5704	- 0.1764	0.6125	0.6839	- 0.0875	0.4705	0.4322
2	- 0.1763	0.5216	0.5177	- 0.1340	0.4056	0.3079	- 0.0950	0.6110	0.6798	- 0.0447	0.4719	0.4432
3	- 0.0458	0.5493	0.5850	- 0.0687	0.4018	0.3098	0.0456	0.6460	0.7878	0.0225	0.4835	0.4842
4	- 0.0209	0.5272	0.5375	- 0.0899	0.4007	0.3066	0.0508	0.6186	0.7137	- 0.0049	0.4736	0.4579
5	- 0.0578	0.5231	0.5260	- 0.1031	0.4022	0.3077	0.0077	0.6110	0.6919	- 0.0254	0.4731	0.4538
6	- 2.4467	2.4467	7.0452	- 0.6859	0.7212	0.7715	- 3.2044	3.2044	11.9181	- 1.4797	1.4820	2.7502
7	- 0.0248	0.5084	0.5020	- 0.0585	0.3963	0.3019	0.0509	0.6040	0.6835	0.0284	0.4676	0.4374

(*) $\hat{\sigma}_6 = \hat{\sigma}_{AM}$ is the classical moving range estimator; $\hat{\sigma}_7 = s$ is the classical standard sample deviation.

Table 5 – Average results for the geostatistical and classical estimators of the standard deviation of the process as a function of σ_a.

		AR			ARMA		
σ_a	$\hat{\sigma}_i$	*ME*	*MAE*	*MSE*	*ME*	*MAE*	*MSE*
2	1	- 0.0237	0.2832	0.1520	0.0224	0.5329	0.7665
	2	- 0.0177	0.2845	0.1540	0.0553	0.5325	0.7763
	3	0.0361	0.3054	0.1774	0.1428	0.5638	0.8733
	4	0.0429	0.2946	0.1657	0.1967	0.5583	0.8735
	5	0.0076	0.2876	0.1530	0.1053	0.5245	0.7253
	6	- 0.2145	1.3358	2.5749	- 0.3144	2.3895	10.5233
	7	0.0509	0.2868	0.1636	0.1935	0.5526	0.8580
3	1	- 0.0229	0.4152	0.3316	0.0311	0.7627	1.4979
	2	- 0.0112	0.4161	0.3346	0.0795	0.7647	1.5192
	3	0.0690	0.4535	0.3983	0.2009	0.8142	1.7217
	4	0.0795	0.4400	0.3763	0.2810	0.8119	1.7383
	5	0.0264	0.4286	0.3424	0.1482	0.7591	1.4371
	6	- 0.3150	1.9818	5.7008	- 0.5067	3.5429	22.9923
	7	0.0909	0.4284	0.3640	0.2858	0.8046	1.7475
4	1	- 0.0356	0.5660	0.6506	0.0555	1.0526	3.0655
	2	- 0.0221	0.5702	0.6629	0.1239	1.0576	3.1420
	3	0.0912	0.6156	0.7784	0.2964	1.1361	3.6183
	4	0.1086	0.5962	0.7352	0.4058	1.1232	3.5922
	5	0.0372	0.5782	0.6633	0.2243	1.0511	2.9407
	6	- 0.4496	2.6911	10.7485	- 0.5989	4.8039	43.1554
	7	0.1251	0.5842	0.7263	0.4028	1.1021	3.5077
5	1	- 0.0667	0.7098	0.9581	0.0264	1.2580	4.1816
	2	- 0.0538	0.7117	0.9606	0.1082	1.2630	4.2568
	3	0.0796	0.7589	1.0925	0.3220	1.3619	4.9229
	4	0.0964	0.7338	1.0247	0.4554	1.3399	4.8579
	5	0.0079	0.7166	0.9442	0.2354	1.2588	4.0141
	6	- 0.5139	3.3379	16.1486	- 0.8598	5.8936	63.5967
	7	0.1210	0.7226	1.0271	0.4447	1.3055	4.7462
6	1	- 0.0905	0.8391	1.3514	0.0747	1.5422	6.1699
	2	- 0.0665	0.8444	1.3676	0.1789	1.5454	6.2524
	3	0.1058	0.9154	1.6141	0.4219	1.6432	7.0560
	4	0.1230	0.8868	1.5326	0.5889	1.6352	7.1192
	5	0.0170	0.8667	1.4040	0.3151	1.5236	5.8177
	6	- 0.6564	3.9639	22.7816	- 0.9438	7.1322	92.6429
	7	0.1372	0.8641	1.4957	0.5983	1.6235	7.1873
7	1	- 0.0779	1.0132	1.9667	0.0041	1.8041	8.7616
	2	- 0.0573	1.0157	1.9691	0.1235	1.8092	8.8877
	3	0.1479	1.0991	2.3484	0.4312	1.9319	10.0389
	4	0.1704	1.0734	2.2310	0.6127	1.9265	10.1370
	5	0.0420	1.0364	1.9878	0.2977	1.8090	8.2329
	6	- 0.7264	4.6872	32.0489	- 1.2109	8.2380	125.4821
	7	0.1929	1.0529	2.2022	0.5953	1.8946	10.1568

(*) $\hat{\sigma}_6 = \hat{\sigma}_{AM}$ is the classical moving range estimator;
$\hat{\sigma}_7 = s$ is the classical standard sample deviation.

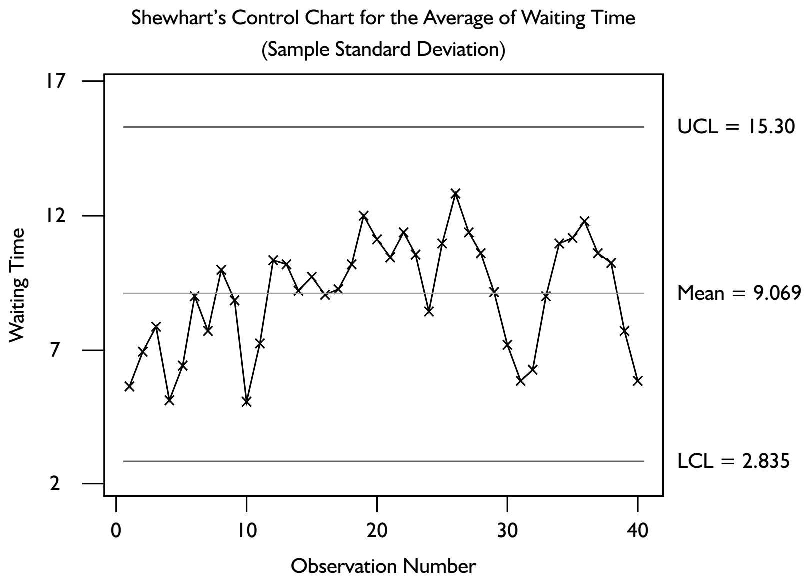
Table 6 – Average results for the geostatistical and classical estimators of the standard deviation of the process as a function of *n* (positive correlation).

		AR (1)			ARMA (1,1)		
n	$\hat{\sigma}_i$	ME	MAE	MSE	ME	MAE	MSE
25	1	- 0.1047	0.8810	1.6116	0.0624	1.4900	6.3739
	2	- 0.0777	0.8863	1.6219	0.1732	1.5023	6.5316
	3	0.1038	0.9381	1.8308	0.3697	1.5676	7.0518
	4	0.1352	0.9040	1.7246	0.5916	1.5669	7.1198
	5	0.0002	0.8722	1.5255	0.2512	1.4274	5.4412
	6	- 0.3946	3.1806	17.5410	- 0.3650	5.7222	70.7773
	7	0.1961	0.9107	1.8032	0.6759	1.5886	7.4756
50	1	- 0.0389	0.6033	0.7235	0.0469	1.1244	3.7361
	2	- 0.0277	0.6058	0.7311	0.1222	1.1281	3.7905
	3	0.1004	0.6628	0.9067	0.3509	1.2284	4.5496
	4	0.1098	0.6456	0.8600	0.4490	1.2188	4.5964
	5	0.0396	0.6289	0.7938	0.2705	1.1511	3.8849
	6	- 0.4914	2.9513	14.3296	- 0.7816	5.2984	58.1726
	7	0.1076	0.6223	0.7957	0.4090	1.1853	4.4118
100	1	- 0.0150	0.4290	0.3702	- 0.0022	0.8619	2.1116
	2	- 0.0089	0.4292	0.3715	0.0393	0.8559	2.0950
	3	0.0606	0.4731	0.4671	0.1870	0.9295	2.5142
	4	0.0654	0.4629	0.4482	0.2296	0.9118	2.4430
	5	0.0293	0.4560	0.4281	0.1413	0.8846	2.2578
	6	- 0.5520	2.8670	13.1310	- 1.0707	4.9793	50.2466
	7	0.0552	0.4365	0.3906	0.1753	0.8676	2.2144

(*) $\hat{\sigma}_6 = \hat{\sigma}_{AM}$ is the classical moving range estimator;
$\hat{\sigma}_7 = s$ is the classical standard sample deviation.

Table 7 – Customers waiting time data.

Customer	Waiting time	Customer	Waiting time
1	5.60	21	10.44
2	6.94	22	11.37
3	7.85	23	10.52
4	5.10	24	8.44
5	6.40	25	10.93
6	9.00	26	12.79
7	7.70	27	11.38
8	9.96	28	10.59
9	8.82	29	9.12
10	5.04	30	7.18
11	7.25	31	5.84
12	10.32	32	6.27
13	10.16	33	8.99
14	9.20	34	10.96
15	9.70	35	11.18
16	9.05	36	11.80
17	9.27	37	10.61
18	10.20	38	10.21
19	11.96	39	7.67
20	11.13	40	5.82



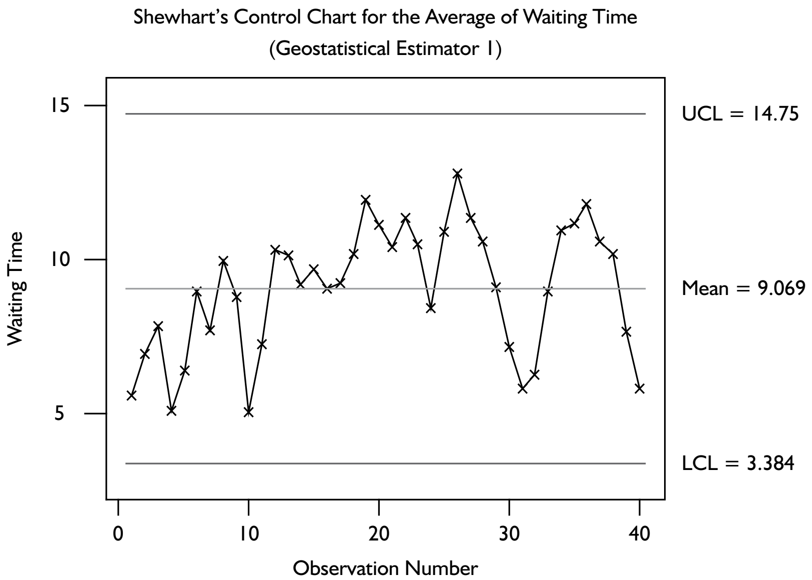


Figure 1 – Shewhart's control charts for the average of customers waiting time.

Table 8 – Semivariogram and autocorrelation estimates waiting time - queuing system example.

h	$\hat{\rho}h$	$\hat{\gamma}h$	h	$\hat{\rho}h$	$\hat{\gamma}h$
1	0.6024	1.4279	11	4.4173	1.4279
2	0.2152	3.0966	12	4.9501	3.0966
3	0.1187	3.5818	13	4.6301	3.5818
4	- 0.0861	4.3997	14	4.5139	4.3997
5	- 0.1082	4.4114	15	4.6467	4.4114
6	0.0909	3.4886	16	4.9387	3.4886
7	0.1777	3.0692	17	5.5341	3.0692
8	0.1958	3.0572	18	6.1187	3.0572
9	0.1612	3.2162	19	5.3455	3.2162
10	0.0388	3.5668	20	4.8959	3.5668

Table 9 – Estimates of the standard deviation waiting time example.

Estimator	**Estimate**
Geostatistics 1	1.8950
Geostatistics 2	1.9819
Geostatistics 3	2.0409
Geostatistics 4	2.0433
Geostatistics 5	2.0206
Moving range	1.2513
Sample standard deviation	2.0783

Concluding Remarks

In this paper we presented new estimators for the variance and standard deviation of autocorrelated processes based upon the concepts of Geostatistics methodology. In the presence of correlation this estimation procedure is very appealing because it allows the user to keep monitoring the quality of the process by using the usual Shewhart's control charts. It was shown that in general the geostatistical estimators $\hat{\sigma}_1$ and $\hat{\sigma}_2$ had better or similar performance than the classical standard sample deviation s in all simulated cases. In the cases where the classical standard sample deviation s presents better performance than the geostatistical estimators $\hat{\sigma}_3$, $\hat{\sigma}_4$, $\hat{\sigma}_5$, the difference in terms of average error values were not to large. For high negative correlation the estimator $\hat{\sigma}_5$ was the best and for all the other cases the estimators $\hat{\sigma}_1$ and $\hat{\sigma}_2$ had better performance. This paper also shows that the classical moving sample range estimator should not be used to estimate the standard deviation of autocorrelated processes. This fact was also pointed out by Mingoti and Neves (2003).

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Alignment of Management Priorities, Manufacturing Flexibility and Performance in Small Companies

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Abstract

Manufacturing flexibility can be used to achieve competitive advantage. Since flexibility is a relative concept, the level of required flexibility is defined by the market, i.e., it is defined by competitors and competitive environment. An important characteristic of manufacturing flexibility is its multidimensionality (dimensions and elements). Manufacturing flexibility has to be analyzed from the point of view of the dynamics of the relationships among its dimensions and the effective response a company has to give to all demands from its competitive marketplace. Depending on the management priorities, some manufacturing flexibility dimensions can be more emphasized and used as a competitive weapon to improve performance. This paper discusses the alignment (meaning the coherence between what is perceived and what is used) of actual manufacturing flexibility, considering the scope and achievability factors of five flexibility dimensions, and important aspects of management priorities and manufacturing performance based on a literature review and on a field work involving five small companies. Some related patterns are identified and show the managers' perspective about these questions in the manufacturing flexibility context.

Keywords: manufacturing flexibility, management priorities, small companies, manufacturing performance

Introduction

Manufacturing flexibility can be defined as an ability (Slack, 1992; Upton, 1994; D'Souza and Williams, 2000; Frazelle, 1986) or capability (Golden and Powell, 2000;

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Zelenovic, 1982) that an organization has to change (Slack, 1992; Upton, 1994) or react when dealing with environmental changes, considering the time, cost, and effort involved (Upton, 1994).

In the manufacturing strategy context, flexibility has been studied as a factor that influences both the strategies and the performance of a firm (examples of recent studies are Kathuria, 2000; Das, 2001; Chang et al., 2003; Pagell and Krause, 2004; Dreyer and Gronhaug, 2004). When flexibility is associated with another source of competitive advantage (e.g. time, cost, quality) its relationships and trade-offs are mentioned as subjects for further studies. The influence of manufacturing flexibility on performance is significant to the competitiveness of a firm.

Several small companies have viewed new opportunities for insertion, growth and expansion in their competitive environment mainly due to the intense process of industrial restructuring that took place in large companies. However, one can notice that if business opportunities are increasing for small companies, requirements for them to remain competitive also increase, while many uncertainties that previously applied only to large companies are being transferred to them. Also, the poor availability of resources and the difficulties in developing new technologies or accessing existing ones lead small companies to search for efficient means to manage their available resources.

Such aspects suggest that small companies should necessarily be more prepared to remain active in the industry. In this sense, manufacturing flexibility can be a key component in competitive advantage for such companies. However, this possibility must be carefully studied, because the adaptive/reactive position of small companies could cause a differentiation in their flexibility requirements, usually making them more intensive in certain flexibility dimensions than in others.

The objective of this study is to analyze the alignment, i.e. the coherence between what is perceived and what is used, between actual manufacturing flexibility considering the scope and achievability of five flexibility dimensions and important aspects of management priorities and manufacturing performance based on a literature review and on a field work involving five small companies. Some related patterns are identified considering the managers' perspective regarding these aspects in the manufacturing flexibility context.

The following conceptual model (Figure 1) shows the linkages among the variables. It will be used to examine general aspects of the alignment of actual manufacturing flexibility (according to the importance given to certain flexibility dimensions) with several management priorities and manufacturing performance aspects. Our analysis is based on the managers' perception and considers the coherence between what is perceived and what is used in order to assess the alignment among these constructs.

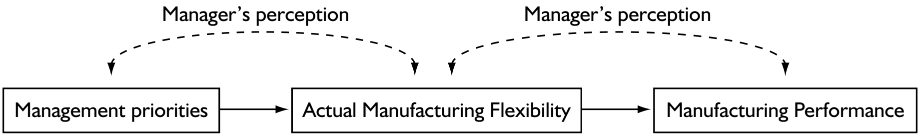

Figure 1 – Conceptual model.

In this study it is primarily hypothesized that companies use manufacturing flexibility by improving specific flexibility dimensions, and according to the importance given to these dimensions the manufacturing performance can be influenced. This study considers only the actual manufacturing flexibility in its scope and achievability factors, because it is supposed to be the type of flexibility that is actually influenced by management priorities defined by companies. In other words, when we consider the implementation of manufacturing flexibility we believe that all implemented flexibility is effectively used by the firm in a dynamic base, so it is linked to the concept of actual flexibility. In order to achieve better performance it is considered that firms will align these three constructs in order to achieve better results. The importance given to specific flexibility dimensions is considered as determinant for the impacts of actual manufacturing flexibility on manufacturing performance.

This paper is structured as following. We first present the nature of manufacturing flexibility as a dynamic concept involving several dimensions, elements, and constituent factors based on a literature review. After that we emphasize the strategic use of manufacturing flexibility with implication on the manufacturing performance. Then we describe the methodological approach used in the data collection. Following that we analyze the conceptual model constructs based on the data collected in the five small companies. Management priorities and manufacturing performance aspects are described as elements that affect the actual manufacturing flexibility, and this is analyzed in terms of the scope and achievability factors.

The Concept of Manufacturing Flexibility

Flexibility is a multidimensional concept composed of several dimensions and elements. A recognized aspect associated with the multidimensionality of flexibility is the fact that a firm being flexible in one dimension does not mean it will be flexible in another (Upton, 1995). This is because of the relationships among flexibility dimensions and elements which can be supportive in nature or produce trade-offs.

Flexibility can be seen from different points of view: required, potential, and actual (Parker and Wirth, 1999; Koste, 1999). Required flexibility is the amount of flexibility that is necessary to be demonstrated by the system in order to respond effectively to the environmental uncertainties and to align flexibility to manufacturing strategy. Potential flexibility is related to the amount of flexibility that a system can potentially achieve to be used. Usually, potential flexibility can be associated to machinery capacity, worker skills, etc. Actual flexibility is the amount of flexibility that the production system has actually used or demonstrated by the time it is measured. Actual flexibility can be improved by using the potential flexibility properly.

Flexibility is dynamic or static depending on the uncertainties in the competitive environment (Hyun and Ahn, 1992). The static aspect of flexibility usually corresponds to the process technology, and the capacity of a manufacturing system in dealing with uncertainty is defined according to fixed product and production structure. As a result, in a changing context, static flexibility is less efficient, except when, for example, Advanced Manufacturing Technology (AMT) is well implemented. On the other hand, the dynamic aspect of flexibility can deal with frequent changes in the competitive environment and is related to the capacity a system has to deal with variation in a non-stationary environment. This dynamics inserts the concept of learning and understanding level of a production system into the flexibility nature. Thus, continuous incremental improvements and knowledge acquisition are some practices associated with the concept of dynamic flexibility and represent a differentiation from the concept of static flexibility.

Also, flexibility can be internal or external (Upton, 1994). Internal flexibility represents the set of capabilities and operation strategies that a company has to respond to environment uncertain (what can be done). External flexibility is a source of competitive advantage that can be seen in a particular context (what can be seen by the marketplace). It corresponds to the different ways a company can respond to, for example, variations in aggregate demand for product, frequent demand for customization, and opportunities to reach market share by improving product mix.

Flexibility Dimensions and Elements

Several studies on manufacturing flexibility have been directed towards conceptual approaches and classifications of flexibility dimensions, such as those by Gerwin (1987), Gupta and Goyal (1989), Shewchuk and Moodie (1998), Koste and Malhotra (1999), and D'Souza and Williams (2000). Among them, the work by Koste and Malhotra (1999) is worth mentioning for their mapping of several definitions found in the literature and the composition of ten dimensions that, according to the authors, are the most important and commonly noted in researches, which represent a consensus in the diverse points of view they listed. Such ten dimensions are flexibilities related to: machine, workforce, material handling, routing, operation, expansion, volume, mix, new products and product modifications. These dimensions are defined in Table 1.

Table 1 – Definitions of manufacturing flexibility dimensions.

	Dimension	Definition
Plant Level (Tier 3)	Expansion	the number and heterogeneity variety of expansions which can be accommodated without incurring high transition penalties or large changes in performance outcomes
	Volume	the extent of change and the degree of fluctuation in aggregate output level which the system can accommodate without incurring high transition penalties or large changes in performance outcomes
	Mix	the number and variety heterogeneity of products which can be produced without incurring high transition penalties or large changes in performance outcomes
	New product	the number and heterogeneity variety of new products which are introduced into production without incurring high transition penalties or large changes in performance outcomes
	Modification	the number and heterogeneity variety of product modifications which are accomplished without incurring high transition penalties or large changes in performance outcomes
Shop floor (Tier 2)	Routing	the number of products which have alternate routes and the extent of variation among the routes used without incurring high transition penalties or large changes in performance outcomes
	Operation	the number of products which have alternate sequencing plans and the heterogeneity variety of the plans used without incurring high transition penalties or large changes in performance outcomes
Individual Resource (Tier 1)	Machine	the number and heterogeneity variety of operations a machine can execute without incurring high transition penalties or large changes in performance outcomes
	Workforce	the number and heterogeneity variety of tasks or operations a worker can execute without incurring high transition penalties or large changes in performance outcomes
	Material Handling	the number of existing paths between processing centers and the heterogeneity variety of material which can be transported along those paths without incurring high transition penalties or large changes in performance outcomes

Source: Adapted from Koste and Malhotra (1999, p. 81).

Koste and Malhotra (1999) proposed a hierarchical classification for manufacturing flexibility dimensions that shows the potential relationships that could exist among them (see Table 1). Further according to this classification the flexibility dimensions can be seen from the internal to the external points of view distributed in several levels (or tiers). The individual resource (tier 1) is the most internal level and it is comprised of machine, workforce, and material handling flexibility dimensions that represent the basic resources used in the manufacturing process. The shop floor level (tier 2) contains the operation and routing flexibility dimensions that have a supportive role in relation to the higher tier (plant level) in the hierarchy. Plant level (tier 3) includes the most external flexibility dimensions: expansion, volume, mix, new product, and modification flexibilities. The flexibility dimensions at the plant level can be used as competitive weapons because they are more visible to the marketplace.

Similarly to the Koste and Malhotra' (1999) hierarchical classification, Suarez et al. (1996) suggested that flexibility dimensions can be organized according to their effects on competitive position of a firm in a market. This classification is in

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accordance with the perception of these dimensions by the customers. They identify two main groups: "first-order" flexibilities and "lower-order" flexibilities. According to them, "first-order" flexibilities are those that directly affect the competitive position of a firm and are represented by dimensions that can be perceived and clearly interpreted by customers (e.g. mix, new product, and volume). "Lower-order" flexibilities are those that have their final competitive effect expressed through one of the first-order flexibilities.

The work by Koste and Malhotra (1999) may be referred to as a summary of current elements of flexibility: range-number, range-heterogeneity, mobility, and uniformity. They define these ones as the constituent elements of flexibility found in the literature. The range-heterogeneity element was introduced by them. Also, there are several relationships and trade-offs that can be considered among these elements (for details see Koste and Malhotra, 2000). Table 2 describes these four elements.

Table 2 – The elements of manufacturing flexibility.

Element	Definition	Comments
Range-Number (R-N)	Represents the number of possible options which a system or resource can achieve.	A resource or system that can operate in a wider range is considered more flexible than a corresponding one with a smaller range. The R-N element represents a strict numerical count of the flexible options.
Range-Heterogeneity (R-H)	Does not consider the number of options, just the degree of difference between them.	In general, greater heterogeneity among the options necessitates a higher level of ability in the organization. Thus, greater heterogeneity would be associated with a more flexible resource or system.
Mobility (M)	Represents the ease with which the organization moves from one state to another.	Corresponds to the 'ease of movement' notion proposed by Slack (1987).
Uniformity (U)	Captures the similarity of performance outcomes within the range.	The less flexible system will exhibit peaks or valleys in performance outcomes. Uniformity can be assessed through a large number of performance measures. These include, but are not limited to, efficiency, productivity, quality, processing times or costs, or product costs.

Source: Created from Koste and Malhotra (2000, pp. 694-695).

Koste et al. (2004) propose two new conceptually separate factors for manufacturing flexibility that are 'scope' and 'achievability' of flexible response. These factors can group all four elements of manufacturing flexibility into two subsets. The scope factor comprises the Range-Number and Range-Heterogeneity elements, and "captures the scope of flexible response in terms of the full range and diversity of options (i.e., operations, products, etc.) that the organization can attain" (p. 182). The achievability factor is comprised of Mobility and Uniformity elements, and "represents the achievability associated with flexible responses" (p. 182). Koste et al. (2004) extend the conceptualization of the achievability factor saying that "it captures the short-term (transient) and long-term (duration) penalties that the organization incurs in invoking the flexible response" (p. 182). These factors will be used in this paper to describe the flexibility dimensions in the five small companies and compare their levels of flexible response.

Also, it is clear that in terms of competitive advantage the main set of dimensions to be considered in a manufacturing strategy is the one that is usually better perceived by customers, i.e., external flexibility (plant level). Internal flexibility still is important and can be seeing as support for the external one. This paper focused on three external flexibility dimensions (mix, new product, and modification) because they are directly related to a firm's competitiveness (Chang, 2003), and on two internal dimensions (workforce and machine). Since actual flexibility is the main subject of empirical research (Koste, 1999) this study also focus on it.

In the following sections we describe the methodological approach for the field study, and the analysis of the alignment of management priorities, manufacturing performance, and actual manufacturing flexibility according to the managers' perspective.

Research Methodology

In addition to the literature review, which included recent researches related to manufacturing flexibility, a field study was conducted involving five small companies selected from the Metal Mechanics sector in Rio de Janeiro. Table 3 shows the general characteristics of each company.

Table 3 – The five selected small companies.

	Company A	Company B	Company C	Company D	Company E
Main activity	Electromechanical equipment	Milling Boiler factory	Milling Boiler factory	Milling Boiler factory	Micro Milling
Production System	1% Make to order 99% Assemble to order	3% Make to stock 94% Make to order 3% Assemble to order	100% Make to order	98% Make to order 2% Assemble to order	20% Make to stock 80% Make to order
Approx. Number of Employees	25	10	48	21	60
Location	Rio de Janeiro - RJ	Niterói - RJ	Cordeiro - RJ	Cordeiro - RJ	Nova Iguaçu - RJ

The data collection was based on visits to the plants and interviews with the companies' managers. Before the interview, each company was visited in order to observe some production environmental characteristics that could be explored during the interview. An important aspect of the interviews was that some concepts related to manufacturing

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flexibility were previously clarified in order to avoid any misunderstanding or personal interpretation about them that could be divergent (e.g. definitions to manufacturing flexibility dimensions).

For the data presented in this study, we used a structured questionnaire to obtain general information about the management priorities, the importance given to ten dimensions of manufacturing flexibility, and the implementation of main flexibility dimensions according to the managers' perception. The questionnaire was adapted from the one used by Koste (1999), and some new items were included. The grades use 5-points and 7-points Likert scales. Figure 2 to Figure 9 use 5-points scale that stands for: 1) not important; 2) of some importance; 3) important; 4) very important; and 5) extremely important. Table 5 to Table 10 use 7-points scale that stands for: 1) strongly disagree; 2) moderately disagree; 3) slightly disagree; 4) neither agree nor disagree; 5) slightly agree; 6) moderately agree; and 7) strongly agree.

Management Priorities in the Companies

Concerning management priorities related to production, some positioning definitions are directed towards search for flexibility. Among them, there is greater customization in the sense of fulfilling customer expectations and providing customized products, the ability to introduce new products quickly in production, the ability to quickly adjust production capacity, and the ability to effect changes in the products (even after having started production). The degree of importance, according to the scale mentioned above, given to each of these items, as well as their mutual relations and influences, can characterize the level of affinity (or coherence) between what is perceived and what is prioritized in the search for competitiveness, via manufacturing flexibility, by the companies. For such visualization to be possible among the selected companies, several statements regarding to management priorities (see Figure 2) were presented to each manager, who was asked to inform the degree of importance that each represents to their company. From Figure 2 we can draw the following considerations.

Each management priority was considered at least 'important' (level 3) by the companies' managers. Both for Company C and D all priorities listed were classified 'extremely important'. With a slightly differentiated view, for Company E all of these priorities were considered 'very important'. Generally, the managers' perceptions have shown reflexes of the companies' competitive positioning, as well as characteristics of their productive processes.

Almost unanimously, manufacturing customized products according to customer specifications was declared as the companies' most important priorities. This is certainly due to the fact that a large part of the companies' production is made on demand.

With the frequency of new projects/products being requested and demand growth, the companies have been feeling the need to develop more abilities both in the introduction

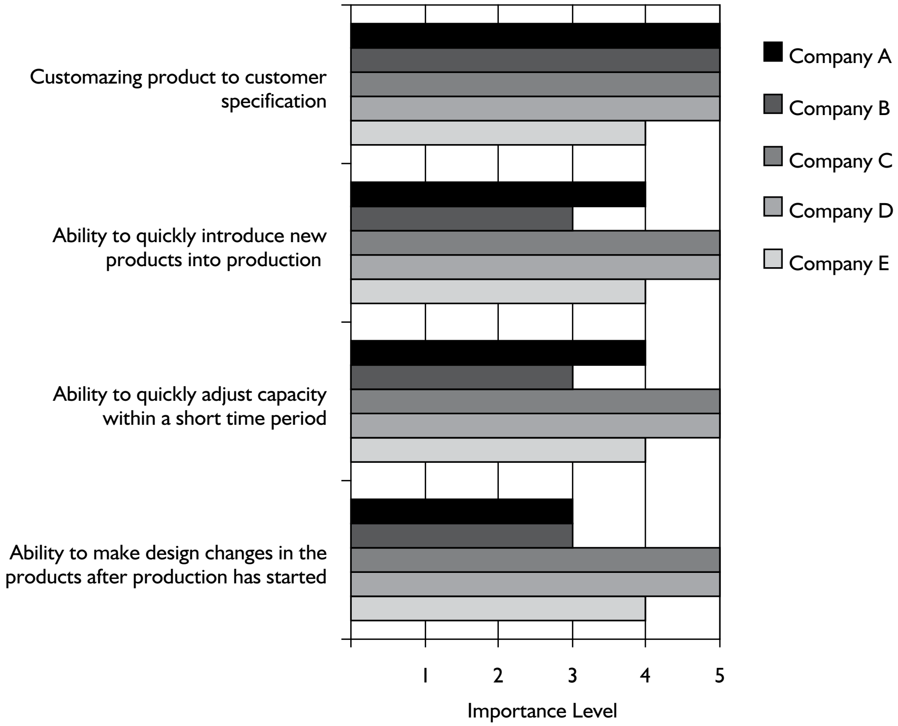

Figure 2 – Degree of importance of diverse management priorities in the production.

of new products into production and in the quick adjustment of capacities. This can be observed with the similarity of the graphs that represent these two management priorities in Figure 2.

The analysis from Figure 2 shows that the companies are interested in all management priorities related to manufacturing flexibility. It is an important result that shows managers interested in remaining competitive in dealing with several demands created by the marketplace. Although it is quite important for being aligned with manufacturing flexibility, the managers have to guarantee that their production systems can effectively and efficiently respond to these demands, so that they can use flexibility in a competitive manner. The high levels attributed to the management priorities represent an important aspect in searching for competitiveness via manufacturing flexibility.

Manufacturing Performance in the Companies

Manufacturing performance can be assessed in many different points of view. For example, Das (2001) used a scale based on dimensions of cost, quality, delivery, manufacturing cycle time, customization responsiveness and new product introduction.

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For the purpose of this study we assess general aspects of manufacturing performance according to the manager's perception of its importance level. The propositions in the scale were based on the work of Koste (1999).

In relation to manufacturing performance dimensions some expected aspects can be brought to light, such as: assurance of product quality consistency and its perception by customers, product cost, cycle time from order to delivery, cycle time to execute variations in the products (according to customer requests), workforce productivity, the company's production capacity, and the variety of products offered. Figure 3 shows the several propositions presented to each manager to be stressed the degree of importance each aspect represents to their company.

In Figure 3, one can notice that for all companies the elements related to manufacturing performance dimensions are considered as being at least 'of some importance' (level 2), in some cases being 'extremely important' (level 5). Elements related to quality assurance (consistency and perception) and cost reduction of products are the ones mostly desired by the companies ('very important' or 'extremely important'), since they are mostly noticed by customers. However, three managers stated that they are concerned in keeping a balance among these performance dimensions, but prioritizing quality. Although cost reduction is desired by companies, this dimension is often less prioritized in an attempt to fulfill time demands, for the main customers of the selected companies usually have productive processes that cannot be interrupted. Therefore, they usually do not demand lower prices, but better quality and trustworthiness instead.

Concerning the time performance dimension, both elements mentioned – reduction of the time cycle from order to delivery and reduction of the cycle time for the execution of variations in the products – were placed at different average levels. The first was considered 'very important' by Companies A, B, D and E and 'extremely important' by Company C. Once again, the consideration of critical supply to the main customers is significant to indicate the importance levels of such elements.

Increasing workforce productivity was placed as 'very important' by Company A, B and C, and 'extremely important' by Company D and E. It is worth noting that this goal is seen with caution by the managers, especially concerning the maintenance of the products' quality levels, usually considering the possibility of loss should productivity be increased without adequate quality control.

Regarding increasing production capacity, the answers were diverse. Generally, considerations were based on the conditions of demands (both current and future perspectives). Company E, for instance, has a high demand on its products, which has encouraged the company to acquire modern equipment that allows reducing setup times between operations in order to increase its productive capacity.

Offering a broader variety of products is considered 'extremely important' by Company E, notably due to the diversity in part requests by its customers. For Company B and D, this

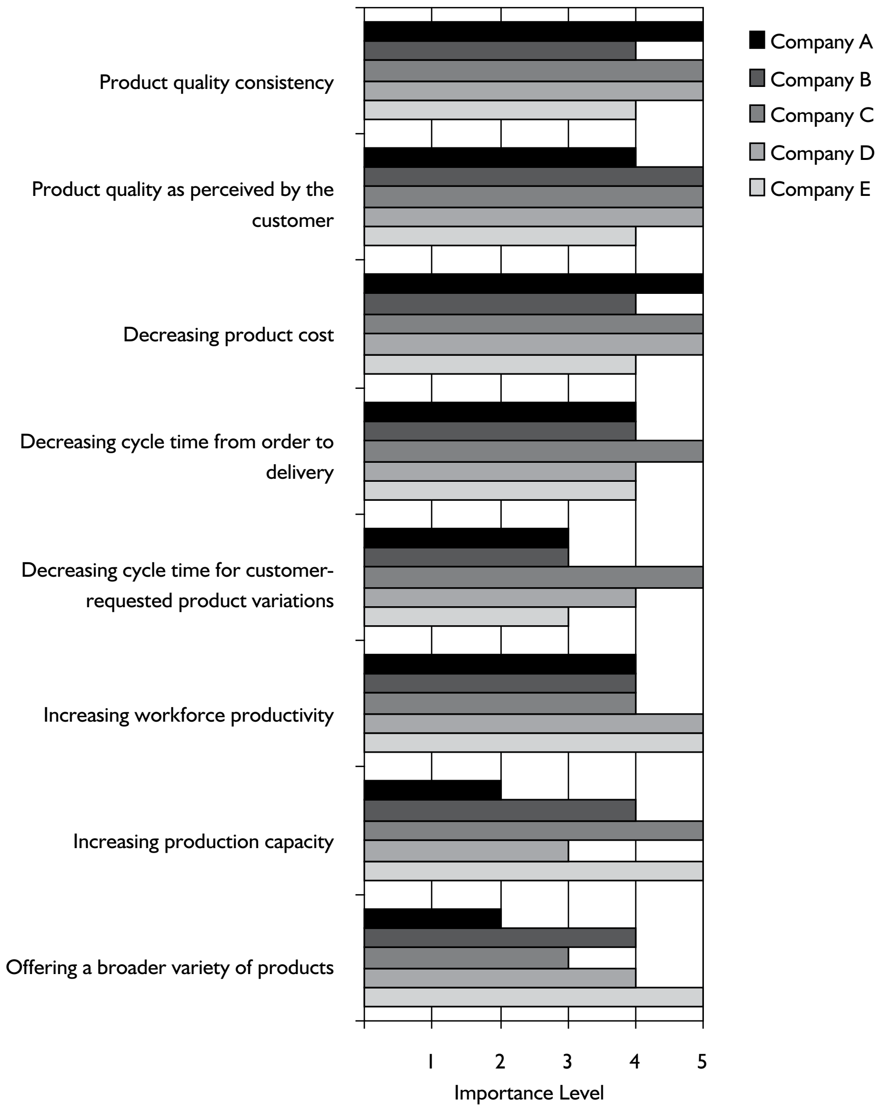

Figure 3 – Degree of importance of elements related to manufacturing performance dimensions.

element is 'very important', although they do not have a defined product line, since their production is almost completely make-to-order.

The answers showed that managers are quite interested in maintaining best results in terms of manufacturing performance. The fact that they gave more importance for those elements related to external response to the marketplace also represents an important view to be considered in analyzing manufacturing flexibility. Once they emphasize several aspects at the same time, they have to be careful in doing it in order to avoid loss in terms of performance due to several trade-offs that can occur among these aspects. For example,

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since they highly emphasized the importance of quality aspects they can incur in a trade-offs between quality, cost, and flexibility, i.e., while they emphasize higher levels of quality it can be hard to ensure higher levels of flexibility without increasing costs.

The Implementation of Manufacturing Flexibility Dimensions

To verify if the companies are actually acquiring flexibility and improving their manufacturing performance, we can analyze first the importance given to several flexibility dimensions, and finally their effective use of such dimensions.

Small companies usually have characteristics that suggest a differentiated behavior concerning manufacturing flexibility needs compared to larger companies (which have been the focus of most studies on flexibility). One might suppose that the relations among flexibility dimensions in small companies also occur in a particular way. For such, the perception and implementation of manufacturing flexibility dimensions were analyzed in the five selected small companies. Among the results, Figure 4 shows the level of importance attributed by managers to the ten flexibility dimensions proposed by Koste and Malhotra (1999) (see Table 1 for definitions). Such attributions suggest diverse aspects of relationships among the dimensions in small companies.

Concerning the hierarchical placement of the dimensions, Figure 4 shows that workforce flexibility was given greater and more consensual importance. Such aspect was expected, since small companies tend to be intensive in workforce. Managers have stated that this dimension is actually considered as a base for others dimensions to operate.

Dimensions at the shop floor tier in Koste and Malhotra's (1999) hierarchy were considered of small relevance by most small companies studied. On the other hand, plant dimensions were placed in higher importance levels due to their effects on the companies' competitiveness, especially because of the better perception and interpretation of such dimensions by customers. This is interesting because it suggests that small companies view these dimensions in the same level, demonstrating a tendency to develop them jointly in the productive environment. This view related to plant tier dimensions is reinforced by the consideration made by Suarez et al. (1996) that product mix, volume, and new products are dimensions of first order and therefore have great influence on the competitive position of companies.

We selected some of those flexibility dimensions considered most relevant in each company to describe them in terms of scope and achievability factors. This selection was based on the availability of measures for these two factors found in the literature. Koste et al. (2004) provide reliable scales for scope and achievability factors for machine, workforce, material handling, mix, new product, and modification flexibility dimensions. We excluded material handling flexibility from our analysis because it was considered of low level of importance by the managers. Table 4 shows the remaining five flexibility dimensions and which companies indicated them as at least "important" (level 3 in our scale).

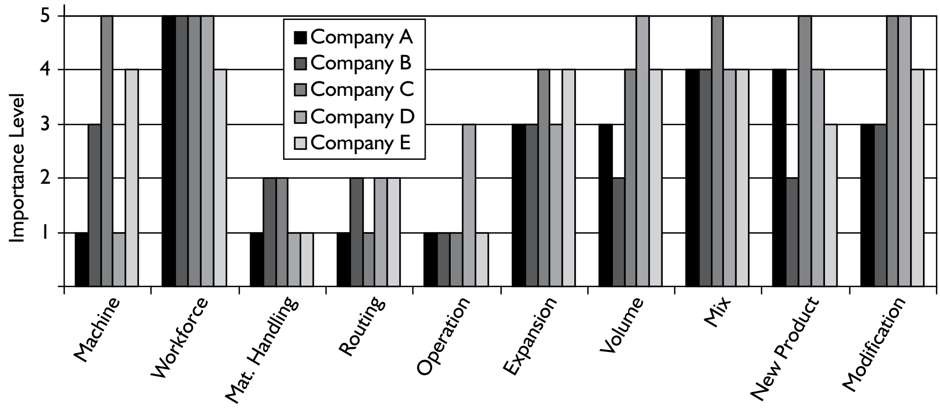

Figure 4 – Importance of manufacturing flexibility dimensions.

Table 4 – Selected flexibility dimensions in each company.

	Company				
	A	B	C	D	E
Machine flexibility		✓	✓		✓
Workforce flexibility	✓	✓	✓	✓	✓
Mix flexibility	✓	✓	✓	✓	✓
New product flexibility	✓		✓	✓	✓
Modification flexibility	✓	✓		✓	

We looked for information regarding to the effective use of these five dimensions by presenting to the managers several specific statements that include the four manufacturing flexibility elements composing the scope (range-heterogeneity and range-number) and achievability (mobility and uniformity) factors. For each statement we asked the managers for positioning their companies in terms of capability in relation to their competitive marketplace by using a 7-points Likert scale.

Machine flexibility

The machine flexibility was considered between 'important' and 'extremely important' for Companies B, C and E. Figure 5 shows the levels of importance for machine flexibility and Table 5 shows the manager's perception on this flexibility dimension.

Companies B and C usually use conventional machines (lathes, etc.), while Company E uses automatic and semi-automatic machines (CNC, etc.) in their manufacturing processes.

The scope factor for machine flexibility

In Company B the machines do not perform a broad range of operations (especially for being conventional machines). That aspect is worst in Company C where according to

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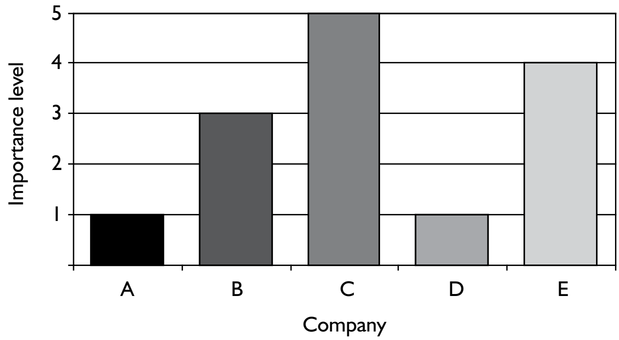

Figure 5 – The importance level for machine flexibility.

Table 5 – The machine flexibility in the companies.

	Company				
	A	B	C	D	E
A large number of operations can be performed by more than one machine.	-	5	1	-	7
Machines can perform operations which differ greatly from one another.	-	6	7	-	7
Machine changeovers between operations are easy.	-	3	1	-	5
Machine tools can be changed quickly.	-	7	6	-	6
All machines achieve similar performance across all operations.	-	3	1	-	5
Machines are equally effective, in terms of productivity, for all operations.	-	3	1	-	5
Machines are equally effective, in terms of quality, for all operations.	-	5	3	-	4
Machines are equally reliable for all operations.	-	5	3	-	4

Note: 1) strongly disagree; 2) moderately disagree; 3) slightly disagree; 4) neither agree nor disagree; 5) slightly agree; 6) moderately agree; and 7) strongly agree.

its manager the machines have a limited range of operations they are able to perform. A different view is presented by Company B where machines individually can perform several operations necessary to the production process of its products. In Company E a higher level of automation allows machines to perform almost all operations to produce its main products.

According to the managers of the three companies analyzed, their machines have a great ability to perform operations that are very different from each other. However, in Company B and C, specially the last one, the changes between operations have some difficulty to be completed, although the manager considers that the machine tools can be changed rapidly. In Company E, in spite of the presence of several automatic and semi-automatic machines the manager admitted the possibility of a delay during changes in machine tools.

The achievability factor for machine flexibility

From the point of view of Company B the machines, while considering the range of operations, do not present most similarities in performance, even most of the time they are equally efficient in terms of productivity. For these two aspects the manager in Company C positioned its machines in a low level and the manager in Company E in a moderate level.

In Company B all machines are considered equally effective in terms of quality and similarly reliable in performing all operations. In Company C, quality and reliability can differ among machines, what incur in caution while defining the operation schedule. The manager in Company C did not answer this statement.

Workforce flexibility

The workforce flexibility was emphasized in the five companies with high level of importance. Figure 6 shows the level of importance indicated by managers and Table 6 presents the answers for the manager's perception on this flexibility dimension.

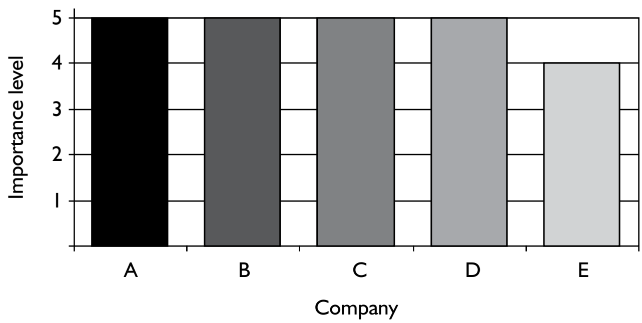

Figure 6 – The importance level for workforce flexibility.

Table 6 – The workforce flexibility in the companies.

	Company				
	A	B	C	D	E
Workers can perform a large number of tasks.	7	6	7	5	6
Workers are responsible for more than one task.	7	6	6	6	5
Workers are cross-trained to perform many different tasks.	7	6	1	7	7
Workers can perform tasks which differ greatly from one another.	7	6	6	4	4
A short time delay occurs when workers are moved between different tasks.	5	6	6	7	4
A small cost is incurred (in terms of lost productivity) when workers are moved between different tasks.	3	5	6	7	4
Workers are equally effective, in terms of quality, for all tasks.	7	4	2	5	5
Workers are equally efficient at all tasks.	2	4	3	5	4
Workers are equally reliable for all tasks.	5	5	3	6	4

Note: 1) strongly disagree; 2) moderately disagree; 3) slightly disagree; 4) neither agree nor disagree; 5) slightly agree; 6) moderately agree; and 7) strongly agree.

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The scope factor for workforce flexibility

Considering the importance of the presence of a qualified workforce, the managers considered that the workers have multiple abilities that allow them to perform a great range of tasks. Further in Companies A, B and C the operations are very different from each other. To ensure, or improve, the variety of abilities of their workers the companies (except Company C) have frequent generalized training process for them. Finally, in each company the workers frequently receive the responsibility for more than one task.

The achievability factor for workforce flexibility

In Company A, although the workers are equally effective in terms of quality while performing their tasks, the same cannot be said in relation to their efficiency in the tasks. In Companies B, D and E these two related statements received similar comments from the managers who said that workers often have low levels of group performance, frequently due to the existence of differences in individual abilities. In Company C the effectiveness in terms of quality and the efficiency in performing the tasks were considered slightly similar among workers. For all companies these aspects certainly do not allow workers to be equally reliable in performing all tasks.

Also from the managers' point of view, the time delay to move workers from one task to another are usually short. However, for Company A the cost in terms of productivity that occurs during this change is relatively high sometimes.

Mix flexibility

The mix flexibility was also emphasized in the five companies. Figure 7 indicates the level of importance attributed by managers in each company and Table 7 shows the answers for the manager's perception on this flexibility dimension.

The scope factor for mix flexibility

There is a great importance for mix flexibility in the five companies. Basically, this importance is due to the make-to-order and assembly-to-order manufacturing processes present in these companies. This implies in a great range of products in each company and very different processing needs for products in Companies A and D in some cases.

The achievability factor for mix flexibility

According to Company A, the product mix can be changed easily and the time necessary to change to a different mix is short. The necessary changes in the production process to deal with the new mix are also fast. Companies C, D and E show similar behaviors in relation to these aspects also considering that sometimes there are several difficulties (mainly in terms of the product type to be produced) that can cause a reduction in agility to complete these changes. This reduction is clear and significant in Company B.

The efficiency of the manufacturing process was declared as not being affected by changes in the product mix in Company A, but the manager agreed that there are significant costs in introducing a new product. In the other companies, the managers admitted that several loss of efficiency can occur in the production process along with rising costs due to the changes in the product mix.

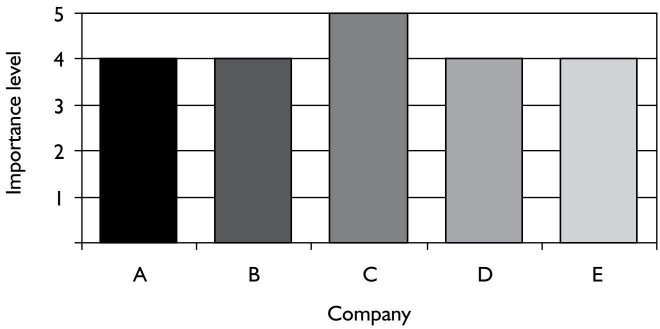

Figure 7 – The importance level for mix flexibility.

Table 7 – The mix flexibility in the companies.

	Company				
	A	B	C	D	E
A large number of products are produced in the plant.	7	5	6	7	7
The processing requirements for the products produced in the plant vary greatly from one product to another.	7	5	2	7	4
The products produced in the plant are very different from one another.	7	6	6	7	4
The cost of including a product in the product mix is small.	5	3	5	6	4
The product mix produced by the plant can be changed easily.	7	3	5	6	5
The time required to change to a different product mix is short.	7	4	5	5	4
The manufacturing system can quickly changeover to a different product mix.	7	4	5	5	5
The efficiency of the production process is not affected by changes in product mix.	7	5	5	5	4

Note: 1) strongly disagree; 2) moderately disagree; 3) slightly disagree; 4) neither agree nor disagree; 5) slightly agree; 6) moderately agree; and 7) strongly agree.

New product flexibility

The new product flexibility was emphasized in all companies, except in Company B. Figure 8 shows the level of importance indicated by managers and Table 8 present the answers for the manager's perception on this flexibility dimension.

The scope factor for new product flexibility

In Companies A and D the number of products introduced into the production process each year is significant, especially due to their make- and assembly-to-order processes. In contrast, the same could not be seen in Companies C and E. In Company C, the number of new products is quite reduced, and in Company E the products are standardized.

Also, all companies admitted that there is a great similarity among new products and existing products (with emphasis in Company A). Furthermore, new products are frequently originated from incremental improvement in existing products.

The achievability factor for new product flexibility

According to the manager in Company A, in some cases the time required to develop and introduce a new product is short. Company A systematically uses CAD technology

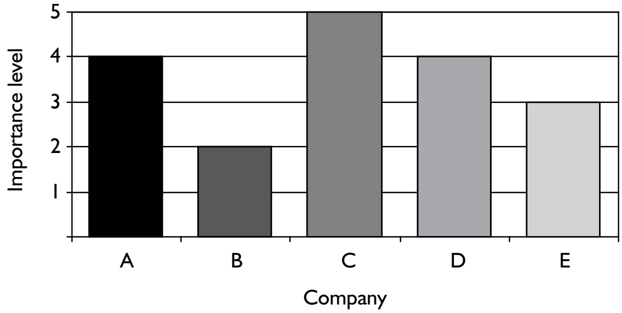

Figure 8 – The importance level for new product flexibility.

Table 8 – The new product flexibility in the companies.

	Company				
	A	B	C	D	E
The number of new products introduced into production each year is high.	6	-	1	5	3
A large proportion of our products have been introduced within the past year.	7	-	2	5	1
New products are very similar to existing products.	7	-	5	5	4
New products are incremental improvements of existing products.	5	-	5	4	4
The time required to develop and introduce new products is extremely low.	5	-	3	2	4
Manufacturing system performance is not affected when a new product is introduced into the production system.	7	-	3	3	4
The quality of existing products is not affected when a new product is introduced into the production system.	7	-	6	7	5
Productivity levels are not affected when a new product is introduced into the production system.	5	-	3	3	5

Note: 1) strongly disagree; 2) moderately disagree; 3) slightly disagree; 4) neither agree nor disagree; 5) slightly agree; 6) moderately agree; and 7) strongly agree.

while developing new products. The use of this technology probably influence this time. We emphasize that the remaining companies usually do not develop new products, because of their make- and assembly-to-order production process nature. Due to this characteristic they usually just receive and execute projects from their customers so their new product flexibility is especially important to introduce these products into the production process (for external needs).

In Company A both the production system performance and the quality of the existing products were declared by its manager not affected when a new product is introduced into the production process. In contrast, managers in Companies C, D and E admit that they always experience loss of performance and quality in their production systems in this case. Furthermore, productivity level also has some loss when a new product is introduced in Companies A and E, also with a slight emphasis in Companies C and D.

Modification flexibility

The modification flexibility was emphasized in Companies A, B and D. Figure 9 shows the level of importance indicated by managers and Table 9 present the answers for the manager's perception on this flexibility dimension.

The scope factor for modification flexibility

Customer specifications and requirements make Company A modify a great number of products. In Company B this number varies greatly; and in Company D only few products are modified. The modified products are in general very different from each other in Companies A and B. Among the occurrences regarding to modifications in products in Companies B and D there are significant similarities with the existing products; in Company A the similarities are less frequent.

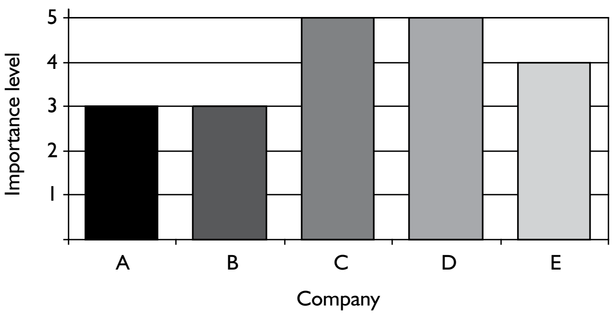

Figure 9 – The importance level for modification flexibility.

Table 9 – The modification flexibility in the companies.

	Company				
	A	**B**	**C**	**D**	**E**
A large number of products are modified to the customer's specifications.	7	4	-	2	-
Modified products are very different from each other.	5	6	-	4	-
Modified products are very different from existing products.	5	2	-	2	-
Modified products can be made quickly.	7	5	-	4	-
The time to produce modified products is small.	3	6	-	2	-
Product modifications are easy to make.	5	6	-	4	-
Manufacturing system performance is not affected by the production of modified products.	5	5	-	6	-
The quality of existing products is not affected when a modified product is introduced into the manufacturing system.	5	6	-	7	-

Note: 1) strongly disagree; 2) moderately disagree; 3) slightly disagree; 4) neither agree nor disagree; 5) slightly agree; 6) moderately agree; and 7) strongly agree.

The achievability factor aspects

The manager in Company A declared that modifications in products can be done quickly, however it can occur some cases in which these modifications intrinsically bring difficulties that make them hard to be completed easily, also with a time increment in the production process for these products. In contrast, in Company B it is easy to make changes in products, usually without any time penalty. In Company D, the necessary time and the agility to make modifications in products vary greatly, but this process usually causes a time penalty in the production system.

Finally, all managers agree that production system performance and quality of their existing products are not significantly affected when a modified product is introduced in production. However, they admit that negative effects in performance and quality can occur even slightly.

The Alignment of Scope and Achievability Factors

Koste and Malhotra (2000) consider the individual contribution of each of the four elements of manufacturing flexibility (range-number, range-heterogeneity, mobility, and uniformity). According to their point of view, greater flexibility is attributed to the resource or system with larger range-number, larger range-heterogeneity, greater mobility, and greater uniformity. This view can be extended to the analysis of scope and achievability factors, considering that a company effectively uses its manufacturing flexibility when it can reach higher levels of both scope (range-number and range-heterogeneity) and achievability (mobility and uniformity) factors. Although it is quite difficult to demonstrate higher levels for both factors (Koste et al., 2004), we can consider that the more a firm acquires improvements in these factors more flexible will it be. We conducted a comparative analysis considering the relative aspect of manufacturing flexibility. Our purpose was to look for differences in terms of scope and achievability factors that can define the level of flexibility in each company. In other words, we analyze the alignment of scope and achievability factors, which means the coherence between what is perceived and what is demonstrated by the companies.

Table 10 shows the average values for scope and achievability factors of the manufacturing flexibility dimensions in the companies. These factors were calculated by averaging range-number and range-heterogeneity elements for obtaining the scope factor, and averaging mobility and uniformity elements for obtaining the achievability factor. We can consider these values to better differentiate the companies in terms of flexible response.

Considering that all dimensions present in Table 10 were considered at least 'important' (see Figure 4 for importance levels), we can get some insights from this table. Looking at the implementation of flexibility dimensions in Company A, we can observe that for workforce, new product, and modification flexibilities the scope factor exceed the achievability

Table 10 – Average values for scope and achievability factors of flexibility dimensions.

Machine	**Group Average**	**Company**				
		A	**B**	**C**	**D**	**E**
Scope	5,5	-	5,5	4,0	-	7,0
Achievability	3,9	-	4,3	2,5	-	4,8
Workforce	**Group Average**	**Company**				
		A	**B**	**C**	**D**	**E**
Scope	5,8	7,0	6,0	5,0	5,5	5,5
Achievability	4,7	4,4	4,8	4,0	6,0	4,2
Mix	**Group Average**	**Company**				
		A	**B**	**C**	**D**	**E**
Scope	4,8	-	5,0	4,0	-	5,5
Achievability	4,6	-	4,2	5,2	-	4,3
New Product	**Group Average**	**Company**				
		A	**B**	**C**	**D**	**E**
Scope	4,4	6,3	-	3,3	4,8	3,0
Achievability	4,5	6,0	-	3,8	3,8	4,5
Modification	**Group Average**	**Company**				
		A	**B**	**C**	**D**	**E**
Scope	4,1	5,7	4,0	-	2,7	-
Achievability	5,1	5,0	5,6	-	4,6	-

factor. It means that Company A invests more in creating options. Yet Company A has poor performance in considering its achievability factor for workforce flexibility which is even lower than the average value for the group. In contrast, the achievability factor exceeds the scope factor for some dimension in four companies (except Company A). It can mean that these companies show superior performance in terms of flexible response, even using fewer resources (less scope in terms of flexible options) to generate their responses to those flexibility dimensions.

Another interesting insight shows that although Company E has automated machines, consequently high scope factor, this company has a low value for the achievability factor, i.e., low performance. It can mean either an alert that automation is not a guarantee of flexible response or that automation is not correctly managed in this company.

Also, we considered the perception of the "overall flexibility" defined in each company by their managers. The standings used for overall flexibility were: 1) Highly Inflexible; 2) Inflexible; 3) Neither Inflexible nor Flexible; 4) Flexible; and 5) Highly Flexible. Table 11 shows the managers' answers. Company C rated its overall flexibility as "highly flexible" (level 5) (see Table 11). Yet Company C is below the average value for scope and achievability factors in almost all flexibility dimensions (except achievability for mix). In contrast, Company B, which rated itself as 'flexible' (level 4), exceeds group average values in six flexibility factors. The analysis of scope and achievability factors allows us to say that Company B is more flexible than Company C.

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Table 11 – Managers' perception for overall flexibility in each company.

	Overall Flexibility
Company A	Flexible
Company B	Flexible
Company C	Highly Flexible
Company D	Flexible
Company E	Flexible

Conclusions

Studies on the relationships, definitions and trade-offs among flexibility dimensions have become essential, considering that in a practical situation the development of flexibility is influenced by such relations. The increase in competitive advantage by means of manufacturing flexibility largely depends on a better understanding of the mechanisms that rule the relationships among the flexibility dimensions. The present study has discussed important aspects of a manufacturing strategy context that can influence the achievement of higher levels of manufacturing flexibility. These aspects allowed us to have an overview of the manufacturing context the companies were inserted in.

The search for competitiveness based on the flexibility of production systems requires an alignment of several aspects. Management priorities are aspects that correspond to the choices for competing in the marketplace. For a competitive use of manufacturing flexibility the management priorities have to be aligned with the right choices for flexibility dimensions. Our analysis showed that the emphasis on specific management priorities in small companies plays an important role as a prior definition in the search for flexibility. The importance level attributed to manufacturing performance aspects helped us to view the expected outcomes in each small company. The scope and achievability factors helped us to better define the relative position of each small company in relation to its flexible response within the group analyzed.

Finally, in considering the overall flexibility rate provided by the manager in the selected small companies, the results showed that the managers do not have parameters to determine precisely the level of flexibility present in their productive systems, which leads us to believe that such characterizations were based on effective responses to their customers' requests. Although formalized strategies to develop manufacturing flexibility in the companies were not mentioned, the perception of its importance by the managers represents a crucial step towards thinking of achieving it.

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Integrating Materials Flow, Production Control and Quality Control: a Proposal and Case Study

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Abstract

This paper presents a proposal for integrating materials flow, production control and quality control. The proposal is based on three principles: that materials flow must be as simple as possible, that a production control system must be compatible with the production system and that the production pace must take account of demand, capacity and quality. The paper examines the dependent relationship between Production Control (PC) and Quality Control (QC) since this relationship provides opportunities for improving manufacturing performance. A case study performed at the world's largest pencil factory suggests that the proposal contributes effectively to operations management at the shop floor level.

Keywords: shop floor level, Production Control, Quality Control, takt time, cycle time, rejection rate

Introduction

To be competitive, a production system has to meet concurrently the objectives of quality, cost and time (Sipper and Bulfin, 1997). Production Control (PC) determines and regulates (schedules, co-ordinates, commands and monitors) the material flows and activities in a production system in the short term (Burbidge, 1990). Quality Control (QC) is the management function which aims to measure, understand and improve the production

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process in order to produce products to specification. The methodology for QC can be represented by the Deming Control cycle, known as the PDCA (Plan-Do-Check-Act) cycle.

This paper proposes integrating materials flow, PC and QC at the shop floor level so as to achieve their associated manufacturing aims of improving productivity, time and quality. The proposal is the IME (Integrating the Manufacturing elements: materials flow, production control and quality control) strategy composed by three principles:

i) **Materials flow must be as simple as possible** Production flow is the backbone of any production system (Sipper and Bulfin, 1997). Materials flow simplification brings cost, time and quality benefits (Burbidge, 1975);

ii) **The production control system (PCS) must be compatible with the production system.** According to MacCarthy and Fernandes, 2000 some of the most used PC systems are kanban, PBC (Period Batch Control), CONWIP, MRP/MRPII, OPT and PERT/CPM. The choice of an adequate PCS is crucial in manufacturing management; this issue is treated in many references, e.g.: (Goddard, 1982), (Aggarwal, 1985), (Ramsay et al. 1990), (Ptak 1991), (Gstettner and Kuhn 1996), (Miltenburg, 1997), (Little et al., 2000); (MacCarthy and Fernandes, 2000); (Sale and Inman, 2003); (Olhager and Rudberg, 2002) and (Jonsson and Mattsson, 2002). The methodology proposed by (MacCarthy and Fernandes, 2000) has been used to choose a PCS according to production system characteristics; and

iii) **The production pace must take account of demand, capacity and quality.** This principle identifies a dependency between PC and QC that arises because the production pace (rate) influences the rejection rate. This relationship provides opportunities for improving manufacturing management. As (Rummler and Brache, 1990) state: "... the greatest management improvement opportunities are, nowadays, on the processes integration...". An algorithm that considers capacity and quality has been developed for production pace determination.

A review of 55 papers that deal with the PC and QC relationship showed that the majority of these papers use mathematical models that aim to optimise variables such as production batch size and inspection batch size. Examples of these papers are: (Ouyang et al., 2002); (Affisco et al., 2002); (Khouja, 2003); (Ioannidis et al., 2004); (Sheu and Chen, 2004); (Balkhi, 2004); (Rahim and Ohta, 2005). These models are complex and difficult to implement. Only six papers did not optimise variables. These relate: JIT and TQM (Total Quality Management) (Hohner (1988) and Kagemann (1990)), lot size and quality improvement (Inman (1994)), production management and quality management by means of a general model (Jokinen et al. (1995)), quality control and shop floor control (Arentsen et al. (1996) and the performance of production control and the performance of quality control (Van Der Bij and Van Ekert (1999)). None of these papers discuss the influence of the production rate on the rejection rate, a central issue of this paper.

Another important characteristic of this paper is that it identifies the situations where Six Sigma programs have more potential to bring benefits (see Table 2).

Integrating Materials Flow, Production Control and Quality Control

The paper examines the PC and QC processes and the dependency between them. The three principles shown in Figure 1 are now described in greater detail.

Principle I: Materials flow must be as simple as possible

An effective technique for materials flow simplification is to use group or cellular layout. This kind of layout divides components into families and groups machines into cells that may process all the components of a family. (Burbidge, 1975) suggested that the advantages of group layout include reduced throughput time, quality improvement, reduced preparation and handling costs, simplification of paper work, reduced indirect labour, improved human relations, reduced investment per unit of output, reduced set up time and others.

Many papers have been published in the last twenty years dealing with cellular layout formation e.g. 331 papers regarding group technology were found on the Compendex data bank including the papers of Escoto et al. (1998) and Li (2003). Wemmerlöv and Hyer (1986), Selin et al. (1998) and Venupogal (1999) review group technology formation. Selim et al. (1998) classify the papers regarding cell formation into five groups according to the method used for the problem solution. These groups are i) descriptive procedures, which include the well-known components classification and codification and production flow analysis (PFA) methods; ii) Cluster analysis, which includes the paper of Chan and Milner (1982); iii) Graph partitioning, which includes the papers of Rajagopalan (1975) and Mukhopadhyay et al. (2000). iv) Artificial intelligence, which includes the paper by Elmaghraby and Gu (1988); and v) Mathematical programming, which includes the papers by Kusiak (1987) and Shafers and Rogers (1991).

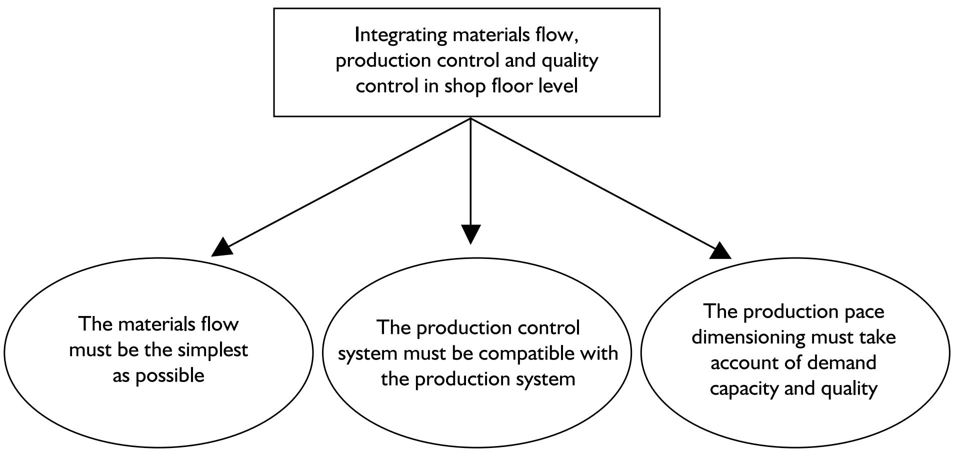

Figure 1 – Principles for integrating materials flow, production control and quality control.

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Within descriptive methods, the two main ways to find the product families and the groups for the development of group layout are by using:

i) Component classification and codification based on the components' sketches; and

ii) Production Flow Analysis (PFA).

PFA uses information from the process sheets, which show how the products are made. According to (Burbidge, 1996a), PFA is better than the component classification and codification methodology which finds the families but does not create the machine groups for these families. PFA on the other hand divides components into families and machines into groups simultaneously at a much lower cost. The case study described later uses the PFA method.

The PFA technique created by Burbidge in the 60's consists of a sequence of sub-techniques. In large companies it starts by simplifying the flow among factories or divisions using Company Flow Analysis (CFA). Next, Factory Flow Analysis (FFA) unites "closely associated processes into sets to form departments before considering the re-allocation of machines between the departments". After this, it divides departments into groups using Group Analysis (GA). The materials flow among the work centres within the group is then studied using Line Analysis (LA). Finally, Tooling Analysis (TA) is used to find the tooling families (groups of parts all of which can be made using the same set up using the same set of tools). The aim is to plan the operation sequencing and find feasible sets of parts for automation. In the case study, the FFA and GA stages were sufficient to obtain the materials flow simplification.

Principle II: The production control system and production systems must be compatible

For each processing unit of the company, this principle aims to choose a compatible production control system. It does this by basing the Production Control System (PCS) choice on the production systems classification methodology developed by (MacCarthy and Fernandes, 2000). They identified twelve variables, namely: repetitiveness level, enterprise size, response time, automation level, product structure, level of customisation, number of products, and the type of buffer, layout, flow, assembly and work organisation that affect the PCS complexity level. Table 1 shows how the choice of an adequate PC system is affected by the variables, the most important being the repetitiveness level. The last line of Table 1 indicates an appropriate PC system based on the repetitiveness level of the production system. A Kanban control system can be used for the repetitive manufacture of items. Period batch control (PBC), described in (Burbidge, 1996b), can be chosen for semi-repetitive production whereas MRP may be necessary for non-repetitive situations. For large projects, PERT/CPM can be the most appropriate choice.

While the repetitiveness level affects the basic PC system choice, the other variables affect the detailing and complexity of the system. Table 1 shows that the Response Time (R) depends on the state in which stock is held. If the system maintains finished product stock, then provided stock is available, R= DL where DL = Distribution Lead-time. If the system produces to order but maintains stock of raw materials, R=PL+DL where PL = the Production Lead-time. If the system produces to order and does not maintain raw material stock, R=SL+PL+DL where SL= Supply Lead-time. If the system assembles to order and maintains stocks of components R=AL+DL where AL= Assembly Lead-time and so on. The type of buffer (1= buffer before the first production stage; 2= buffers between intermediary stages and 3= buffer after the last production stage) and the type of flow (F1= mono-stage; ...; F12= multi-directional multi-stages with unequal machines in parallel) influence the scheduling of the work, and the type of assembly (A1= mixture of chemical ingredients; A2= assembly of a large project; ...; A9= unpaced assembly line) influences line sequencing and line balancing. A more detailed description of Table 1 is provided in (MacCarthy and Fernandes, 2000).

Table 1 – The variables and the choice of a PC system. Source: (MacCarthy and Fernandes, 2000).

Variables	**Description of Production control system**						
Production system repetitiveness	Pure continuous	Semi-continuous	Mass production	Repetitive	Semi-repetitive	Non-repetitive	Large Projects
Enterprise size	**For all levels of repetitiveness, the larger the enterprise, the greater the complexity of production planning and control (PC) activities**						
Response time	DL(a-P%)	DL(a-P%)	DL(a-P%)	DL(a-P%)	PL+DL	PL+DL or SL+PL+DL	SL+PL+DL
Automation Level	Rigid	Rigid	Rigid	Normal or Flexible	Normal or Flexible	Normal or Flexible	Normal
Product structure	**For all levels of repetitiveness, the PC activities for multi-level product structures are more complex than for single-level product structures**						
Level of Customisation	Standard products	Standard or mushroom	Standard or mushroom	Standard or mushroom	Mushroom or semi-customized	Semi-customized or customized	Customized
Number of products	**For all levels of repetitiveness, the PC activities for multi-products are much more complex than for single-products**						
Types of Layout	Product Layout	Product Layout	Product Layout	Group Layout	Group Layout	Functional Layout	Fixed position Layout
Types of buffer	(1) and (3)	(1), (2) and (3)	(1), (2) and (3)	(1), (2) and (3)	(1), (2) or (1)	(1), (2) or (2)	Without buffer
Types of flow	**The complexity of the PC activities increases from (F1) in direction of (F12)**						
Types of assembly	(A1) or disassembly	(A1) or disassembly	(A5) or (A6) or (A7) or no assembly	(A5) or (A6) or (A7) or no assembly	(A7) or (A8) or (A9) or no assembly	(A3) or (A4) or no assembly	(A2)
Types of work organization	**For assembly, work organization directly affects the way the work in the assembly is balanced**						
Appropriate production control system	Spreadsheet to control the rate of flow	Spreadsheet to schedule the work	Kanban	Kanban or PBC	PBC or OPT	MRP	PERT / CPM

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Principle III: The production pace (takt time) must take account of demand, capacity and quality

After simplifying the materials flow (first principle) and choosing the production control system (second principle), the third and main principle is that the production pace is determined by taking into account the demand, the capacity and the influence of the production pace on the rejection rate.

(Sipper and Bulfin, 1997) suggest that production should be pulled using a production pace which establishes a constant production flow This production pace is determined, according to (Womack and Jones, 1996), by the takt time defined as the time that precisely matches the production rate to the customer demand. For (Ohno, 1988), the takt time is obtained by dividing the daily available production time by the quantity of products required in a day. For (Iwayama, 1997), the takt time is the production time allocated for the production of a part or product in a line or in a cell. Each connects the production pace with the demand. However, other factors that should be considered when calculating the production pace are the capacity and the influence of the production pace on the rejection rate. (Antunes, 2001) defines takt time as the necessary production pace to respond to the specific demand level, taking into account line or cell capacity restrictions. In other words, the necessary pace may not be possible due to capacity restrictions. Capacity then influences the production pace. This author distinguishes between takt time and the cycle time in order to clarify the relationship between them. Depending on this relationship, actions may be required to reduce the operation execution time. So (Antunes, 2001) defines line or cell cycle time as the operation execution time on the slowest machine or on the slowest point of the line, the "bottleneck" operation.. For example, if a line has a bottleneck with a minimum cycle time of 5 minutes and if the required production pace is 10/hour, the required takt time would be 6 minutes. On the other hand, to produce 15/hour, the required takt time would be 4 minutes whereas the bottleneck cycle time of 5 minutes would restrict production to 12/hour. The effective takt time is thus the calculated (or nominal) takt time if the capacity is greater than or equal to the demand but is the cycle time when the capacity is less than the demand. Thus:

Effective takt time = maximum (takt time, cycle time)

However, increasing the production pace (i.e. reducing the takt time) to fulfil a certain demand may, even if the capacity allows, increase the rejection rate and reduce the effective production pace and consequently the value flow. In other words Production Control and Quality Control are related. To determine the production pace taking into account this relationship between PC and QC requires knowledge of the takt time v rejection rate curve. This is likely to vary according to the products and the production process. The effective takt time (taking into consideration the demand and the capacity) of the line needs to be compared to this takt time v rejection rate curve for each machine which will be working with this takt time. This effective takt time can be then adjusted so as to reduce the rejection rate and to determine the effective takt time 2. An algorithm for defining effective takt time 2 that depends on the company strategy is now presented.

Algorithm for Defining Effective Takt Time 2

STEP 0: Classify the rejection levels for the machines or production line and for the products into 3 different groups:

- Zero i.e. rejection levels less than or equal to 3,4 parts per million (ppm), which is the aim of six sigma quality;
- Low i.e. rejection levels that are higher than zero but do not harm the production flow of the system; and
- High i.e. unacceptable rejection levels that can interrupt the materials flow.

The rejection level classification depends on the processes/machines/products involved

STEP 1: For a production line, find the line cycle time (balance the line if necessary using, for example, any of the techniques mentioned in (Erel and Sarin, 1998));

STEP 2: Analyse the calculated takt time and the cycle time, using Figure 2. The effective takt time can assume values between the calculated takt time and the cycle time. In this situation increasing the number of employees/improvement cycles could lead to a reduction of the cycle time, but not by enough to make the cycle time equal the calculated takt time. This intermediate value between the calculated takt time and the cycle time is called an improved cycle time.

STEP 3: Define the effective takt time. Figure 2 shows three cases:

i) Effective takt time equals the calculated one (demand is satisfied);
ii) Effective takt time equals the cycle time (some demand is unsatisfied); and
iii) Effective takt time equals an improved cycle time (unsatisfied demand is smaller than (ii)).

STEP 4: Build the rejection rate v takt time curves for all workstations on the production line, using historical data or empirical research.

STEP 5: Find on the rejection rate v takt time curve the rejection rate which is equivalent to the effective takt time found in step 3. Interpolate if necessary.

STEP 6: Use the rejection rate found in step 5 to classify the effective takt time as having: zero, low or high rejection levels (according to step 0). For a production line the line rejection level will be the worst of the machines rejection levels. For example: if the line has three machines one with zero defects, one with low and one with high rejection levels, then for that effective takt time the line rejection level will be high.

STEP 7: Effective takt time 2 definition: This step results in 9 cases that are a combination of the effective takt time definition (step 3) and the classification of rejection levels

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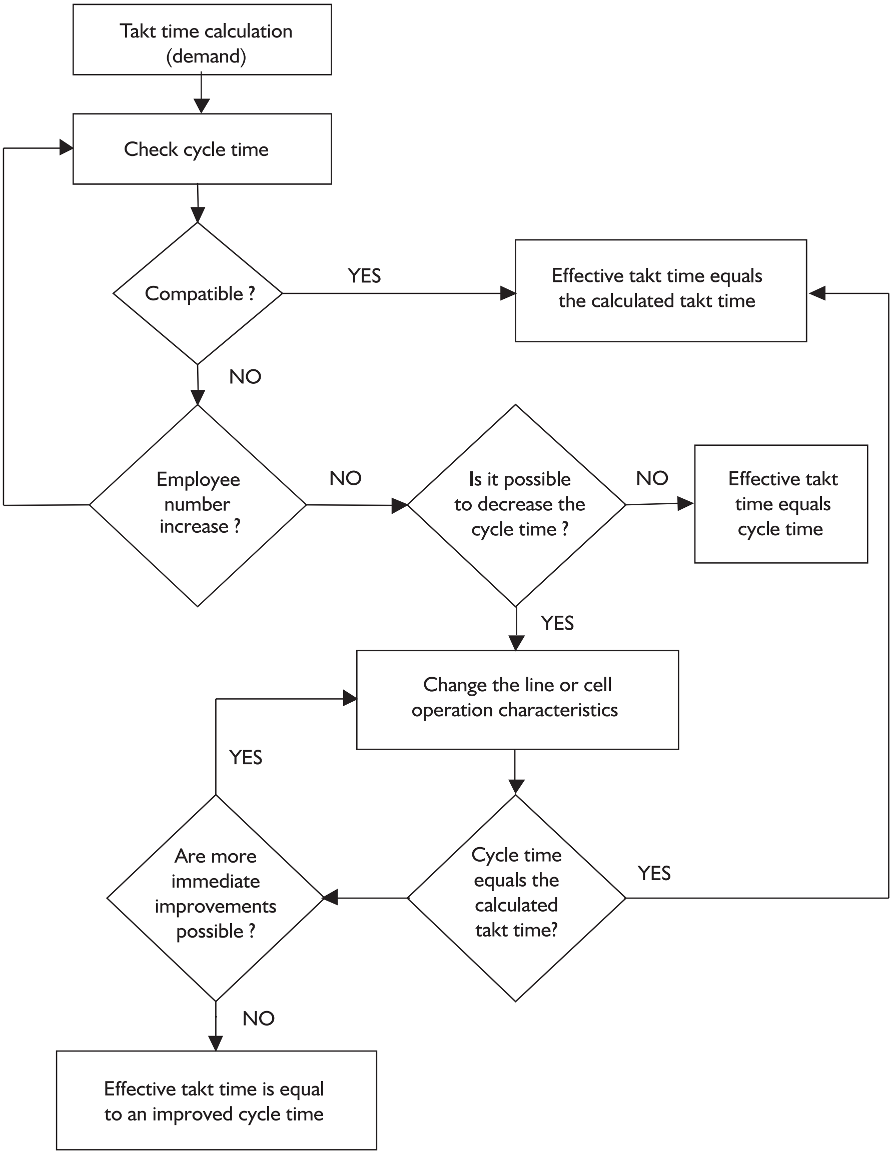

Figure 2 – Effective takt time calculation (taking demand and capacity into consideration).

(step 6). Table 2 shows the 9 possibilities for effective takt time 2 and suggests the action that should be taken for each possibility.

Case Study – An Application of the Proposal

This section applies the three principles to the printing department of the world' largest pencil factory which is situated in Brazil.

Stage 1: Simplify the materials flow as much as possible

The FFA (Factory Flow Analysis) and GA (Group Analysis) stages of the PFA methodology (Burbidge, 1996a) were used to simplify the materials flow. These stages group the items into product families and the machines into groups (group or cell layout). Both stages consist of several steps. Most of these stages are well known and understood and so only the basic results achieved with FFA and GA implementation are shown.

Table 2 – Demand characteristics, rejection characteristics and actions to be taken for each possible effective takt time 2.

Effective takt time 2 equals	Rejection level classification	Demand characteristic	Actions to be taken
Calculated takt time	Zero rejection level	Fulfilled demand	Keep quality standards
Calculated takt time	Rejection which does not harm the flow, but is over the six sigma limits (3,4 ppm)	Fulfilled demand	The rejection rate can be reduced by means of efforts on six sigma/ TQM
An increased calculated takt time due to quality reasons	Rejection which is harmful to the flow (high)	Demand not fulfilled due to quality problems	Urgent action to reduce the rejection rate. While this improvement is not possible, increase the calculated takt time until it reaches the boundary between high and low rejection levels (this will be the effective takt time 2)
Cycle time	Zero rejection level	Demand not fulfilled due to lack of capacity	Keep quality standards; Seek improvements to reduce cycle time (capacity increase – see Figure 2)
Cycle time	Rejection which does not harm the flow, but is over the six sigma limits (3,4 ppm)	Demand not fulfilled due to lack of capacity	The rejection rate can be reduced by means of efforts on six sigma/TQM; Seek improvements to reduce cycle time (capacity increase – see Figure 2)
An increased cycle time due to quality reasons	Rejection which is harmful to the flow (high)	Demand not fulfilled due to lack of capacity and quality problems	Urgent action to reduce the rejection rate. While this improvement is not possible, increase the cycle time until it reaches the boundary between high and low rejection levels (this will be the effective takt time 2); Seek improvements to reduce cycle time (capacity increase – see Figure 2)
Improved cycle time	Zero rejection level	Demand not fulfilled due to lack of capacity	Keep quality standards; Seek improvements to reduce cycle time (capacity increase – see Figure 2)
Improved cycle time	Rejection which does not harm the flow, but is over six sigma limit (3,4 ppm)	Demand not fulfilled due to lack of capacity	The rejection rate can be reduced by means of efforts on six sigma/TQM; Seek improvements to reduce cycle time (capacity increase – see Figure 2)
An increased improved cycle time due to quality reasons	Rejection which is harmful to the flow (high)	Demand not fulfilled due to lack of capacity and quality problems	Urgent action to reduce the rejection rate. While this improvement is not possible, increase the improved cycle time until it reaches the boundary between high and low rejection levels (this will be the effective takt time 2); Seek improvements to reduce cycle time (capacity increase – see Figure 2)

Factory flow analysis (FFA)

FFA codifies the processes (Table 3) and studies the routing of the items along the processes in order to simplify the production flow. The initial materials flow (before FFA implementation) is shown in Figure 3 whereas Figure 4 shows the equivalent materials flow simplified using the FFA technique.

Group analysis

Group analysis allocates machines into manufacturing cells or groups according to similarities in the production routings. The groups and the available machines allocated in each group are shown in Table 4. Figure 5 shows the net encompassing all groups and machines.

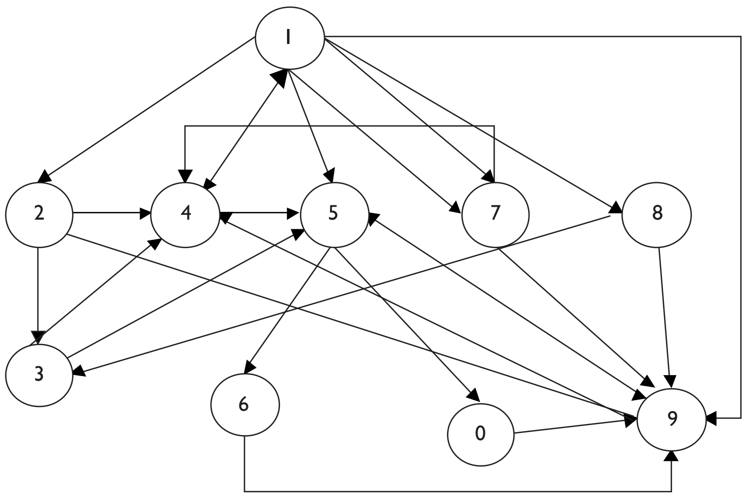

Figure 3 – Initial materials flow net.

Table 3 – Processes code assignment.

Code	Process
1	Cutting – Guillotine
2	Printing 1 – Solna
3	Varnishing
4	Cutting and Creasing
5	Highlighting
6	Pasting 1 – for pasting supermarket items
7	Printing 2 – Roland
8	Printing 3 - Planeta
9	Subcontracted
0	Pasting 2 – for pasting cartridges

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Table 4 – Available machines allocated to each group.

Machines	**Roland Group**	**Planeta Group**	**Solna Group**	**Not Printed Group**
Guillotine	X	X	X	
Roland printer	X			
Planeta printer		X		
Solna printer			X	
Varnisher		X	X	
Cutting and creasing	**Service centre***	**Service centre ***	**Service centre***	**Service centre***
Highlighting	X	X	X	X
Hooker paster	X		X	X
Cartridge paster		X		

* a service centre serves any group which needs its services.

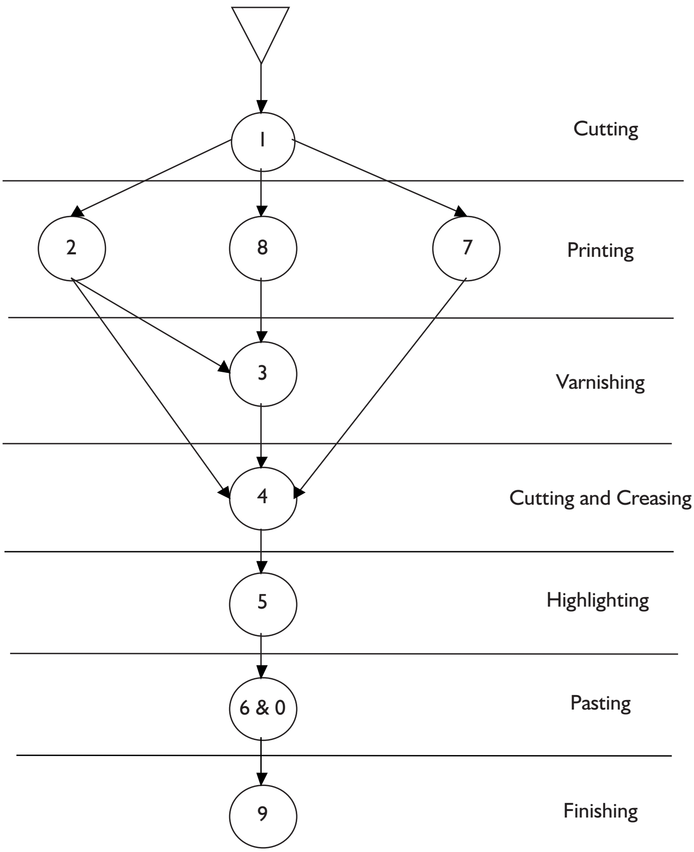

Figure 4 – Simplified materials flow net.

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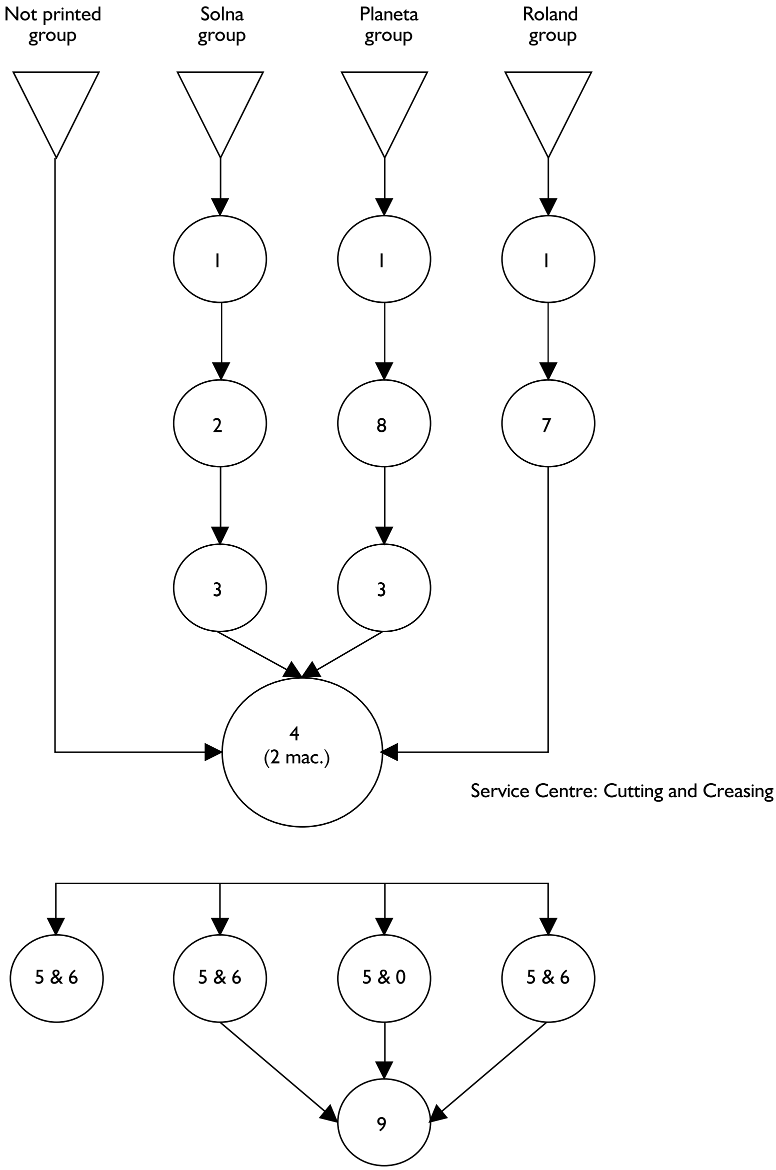

Figure 5 – Net encompassing all groups and machines (including service centre).

Stage 2: Choose the Production Control system (PCS) to match the production system

The multidimensional classification proposed by (MacCarthy and Fernandes, 2000), was used to classify the processing units and to choose a suitable PCS for each one. The four production groups found in the flow simplification performed in stage 1 (Roland, Planeta, Solna and Not printed groups) were classified. The results are shown below. The symbol (/) => (slash) is used to separate dimensions and (_) => (underline) is used to separate variables.

Characterisation
Group General Product Process

Roland: L/PL+DL/NR/N/ML_2_M/G_1-2-3_F4

Planeta: L/PL+DL/NR/N/ML_2_M/G_1-2-3_F4

Solna : L/PL+DL/SR/N/ML_2_M/G_1-2-3_F5

Not printed: L/PL+DL/RP/N/ML_2_M/G_1-2-3_F5

In the classification, L means a large enterprise (more than 500 employees). As there are inventories of raw materials but not of components or final products, the response time is equal to the Production Lead-time (PL) plus Distribution Lead-time (DL). The production systems are respectively non-repetitive (NR), non-repetitive (NR), semi-repetitive (SR) and repetitive production (RP). The automation level is Normal (N); the product structure is multi-level (ML), the level of customisation is 2 (semi-customised) and there are multi-products (M). There is group layout (G) with buffers before the first production stage (1), between intermediary stages (2) and after the last production stage (3) and the types of flow are uni-directional multi-stages (F4) and variable uni-directional multi-stages (F5).

From this classification the most adequate production control system (PCS) for each case is chosen using Table 1. For the Roland and Planeta groups, both non-repetitive systems, the most adequate PCS is MRP. For the Solna group, a semi-repetitive system, the most adequate PCS is PBC or OPT. Finally, for the Not printed group, a repetitive system, the most adequate PCS is Kanban or PBC.

In practice, the company uses MRP for all items. It is the easiest solution, even though it is not necessarily the best. This raises the important but difficult question whether it is better to operate with a single PCS for each processing unit of a production system, or whether is it better to operate with the most appropriate PCS for each processing unit? If a single system is chosen, it would need to be MRP, since it is the only one, which can properly deal with the non-repetitive case. However, it could be less effective than PBC or OPT in the semi-repetitive production unit (Solna group) and worse than Kanban in the repetitive case (Not printed group). On the other hand, operating with a single system may also bring real advantages, for example by avoiding the need to co-ordinate different systems.

Stage 3: Calculate the takt time taking account of the demand, capacity and takt time influence on quality

The takt time is calculated by considering the demand, the capacity, and the takt time influence on the rejection rate. The takt time is the pace at which each item will be produced, pulled by the customers' requirements from the final process of a continuous flow production line. The four groups (Roland, Planeta, Solna and Not printed) were arranged using principle 1 and classified by principle 2. This section deals only with the Not printed group (repetitive system) asit is difficult to use continuous flow for the other groups, which are semi-repetitive and non-repetitive systems.

The Not printed group uses 3 available processes: cutting and creasing, highlighting and pasting. One of them (cutting and creasing) is a service centre. Some characteristics of the three main products (products 1, 2 and 3) of the Not printed group are shown in Table 5 and are used to calculate the production pace.

First, the three processes are checked to see whether they can be connected in any way to obtain a continuous flow among them. However, the cutting and creasing process is a service centre that fits the four groups and so cannot be connected to the highlighting and pasting in a continuous form. Also this process could not be linked in a continuous flow to the highlighting and pasting because of the great difference in the production pace of this process (0.18) compared to the paster pace (1.0; 1.2; 1.8) and the highlighting pace (1.64; 1.16; 1.64).

The highlighting and pasting process times for the three products are similar and so that they can be connected using a continuous flow provided another person is allocated to highlighting for product 1. The cutting and creasing operations can be connected using Kanbans. The highlighting – paster set is used to illustrate the application of our algorithm to determine, by product, the effective takt time 2 taking into consideration demand, capacity and the influence of pace on quality.

Algorithm Application

STEP 0: Table 6 was developed using historical data of interruptions and stoppages to the materials flow. This illustrates, by product and work station, the rejection levels considered low and high.

Table 5 – Demand, production and capacity characteristics for the three studied products in the Not printed group.

Characteristics	Product 1	Product 2	Product 3
Demand (parts/day)	40,000	28,000	12,000
Working hours (per day)	7	7	7
Calculated Takt time	0.63	0.9	2.1
Cutting and creasing production pace (parts/hour)	20,000	20,000	20,000
Cutting and creasing cycle time (seconds)	0.18	0.18	0.18
Highlighting production pace (parts/hour) – 1 person	2,200	3,100	2,200
Highlighting cycle time (seconds)	1.64	1.16	1.64
Paster production pace (parts/hour)	3,600	3,000	2,000
Paster cycle time (seconds)	1.0	1.2	1.8

Table 6 – Rejection levels classification.

Product	Work station	Low rejection level (%)	High rejection level
1	Highlighting	0 - 2	Starting on 2 %
1	Paster	0 – 1.5	Starting on 1,5 %
2	Highlighting	0 – 2	Starting on 2 %
2	Paster	0 – 2	Starting on 2 %
3	Highlighting	0 – 2	Starting on 2 %
3	Paster	0 - 3	Starting on 3 %

STEP 1: Find the cycle time for the production line by product. If necessary, balance the line. Based on Table 5: for product 1, using two employees to work on the highlighting reduces the highlighting cycle time from 1.64 seconds to 0.82 seconds. The line cycle time will then be 1.0 second, the bottleneck time of the paster; the product 2 line is already balanced with a cycle time of 1.2 seconds (paster); the product 3 line is also balanced with a cycle time of 1.8 seconds (paster).

STEP 2: Analyse the calculated takt time and the cycle time for each product according to Figure 2:

- For product 1, the cycle time (1 second) is not compatible with the desired takt time (0.63 seconds). In other words, there is not enough capacity to respond to the desired demand because the cycle time is not compatible with the desired takt time. Then it is checked whether, it is possible to improve the cycle time by using more employees.
  In this case, this is not possible because the bottleneck is the paster, an automated operation. Next an attempt is made to decrease the cycle time is by searching for improvements on the line. Fortunately, some improvements on this specific product's design had already been studied. These were introduced and this reduced the paster's (bottleneck) cycle time to 0.82, the same cycle time as for highlighting. Hence 0.82 seconds became the new line cycle time and the effective takt time;
- For product 2 the line cycle time (1.2 seconds) is greater than, and hence is not compatible with, the calculated takt time (0.9 seconds). Using more employees would not change the line cycle time, as the bottleneck is the paster. The next attempt to decrease the cycle time mentioned in Figure 2 is to search for improvements on the line. For this specific product, immediate improvements seem impossible and so the effective takt time is equal to the cycle time of 1.2 seconds; and
- For Product 3, the calculated takt time of 2.1 seconds is compatible with the line cycle time of 1.8 seconds. In this case the effective takt time is equal to the calculated takt time of 2.1 seconds.

STEP 3: Define the effective takt time for the three products: For Product 1 the effective takt time equals the improved cycle time of 0.82 seconds. Some demand is not satisfied but less than it would be without changes in the cycle time. For Product 2 the effective takt time equals the cycle time of 1.2 seconds and there is some demand loss. For Product

3 the effective takt time equals the calculated takt time (2.1 seconds) and the demand is easily fulfilled.

STEP 4: Create the takt time v rejection rate curves using historical data. The takt time *vs.* rejection rate curves for the three products on the two workstations are shown in Figures 6 to 11.

STEP 5: Use the curves above to design Table 7. This shows for each work station and product the rejection rates that correspond to the effective takt time calculated in step 3:

STEP 6: Based on step 0, Table 8 classifies the rejection levels for the effective takt time, using the rejection rates found in step 5.
In the production line case, a high rejection level is assigned for that takt time if at least one of the work stations present a high rejection level. This was the case on product 2, which although showing a low rejection rate on the highlighting, displayed a high rejection rate on the paster. Therefore there will be a high rejection level if the 1.2 seconds takt time is introduced.

STEP 7: The effective takt time 2 is defined according to the relationship between effective takt time definition (step 3) and the rejection level (defined in step 6). Thus:

- **Product 1:** The work will be done on a line and the effective takt time 2 of the line will be the highest effective takt time of the work stations. The effective takt time is equal to an improved cycle time (0.82 seconds) and from Table 7 it will be seen that the corresponding rejection level is 6.02% i.e. greater than 2% and therefore high according

Table 7 – Rejection rates that correspond to the effective takt time.

Product	Work station	Effective Takt time	Rejection rate
1	Highlighting	0.82 seconds	6.02 %
1	Paster	0.82 seconds	6.80 %
2	Highlighting	1.2 seconds	1.9 %
2	Paster	1.2 seconds	2.7 %
3	Highlighting	2.1 seconds	1.8 %
3	Paster	2.1 seconds	1.7 %

Table 8 – Rejection level determination for the effective takt time.

<table>
<tr><th>Product</th><th>Work station</th><th>Rejection rate</th><th>Takt time</th><th>Classification</th></tr>
<tr><td>1</td><td>Highlighting</td><td>6.02 %</td><td rowspan="2">0.82 seconds</td><td rowspan="2">High rejection level</td></tr>
<tr><td>1</td><td>Paster</td><td>6.80 %</td></tr>
<tr><td>2</td><td>Highlighting</td><td>1.9 %</td><td rowspan="2">1.2 seconds</td><td rowspan="2">High rejection level</td></tr>
<tr><td>2</td><td>Paster</td><td>2.7 %</td></tr>
<tr><td>3</td><td>Highlighting</td><td>1.8 %</td><td rowspan="2">2.1 seconds</td><td rowspan="2">Low rejection level</td></tr>
<tr><td>3</td><td>Paster</td><td>1.7 %</td></tr>
</table>

to Table 6. This is unacceptable. However, if we choose a takt time that corresponds to the boundary of the high and low rejection rates (2% for the highlighting workstation and 1.5% for the paster workstation), the effective takt time 2 for highlighting and paster are 1.57 seconds and 1.68 seconds respectively based on interpolation of data from Figures 6 and 7. The effective takt time 2 for the line will then be 1.68 seconds (the larger of the two). This takt time is much greater than 0.63, the original calculated takt time. In order to reach a takt time of 0.63 an improvement in cycle time (capacity) will be needed. Even more important is that a drastic improvement in the process (aiming to reduce the rejection rate) will be needed.

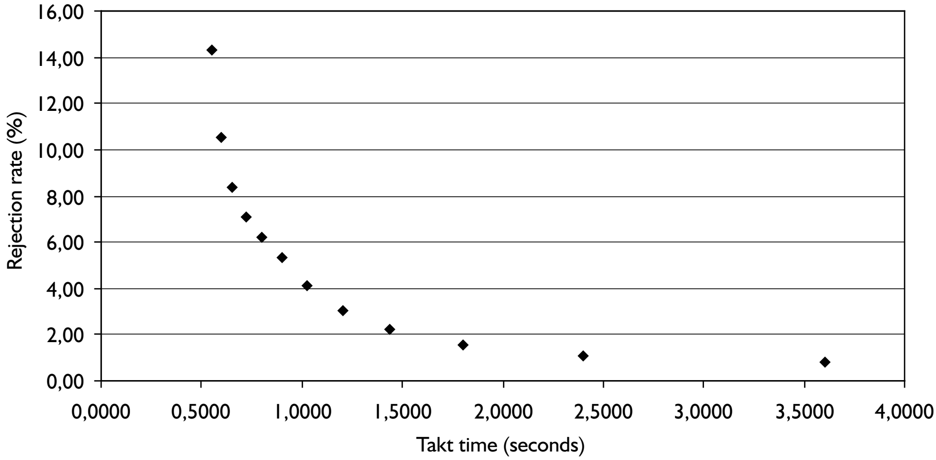

Figure 6 – Takt time *vs.* rejection rate for product 1 on the highlighting work station.

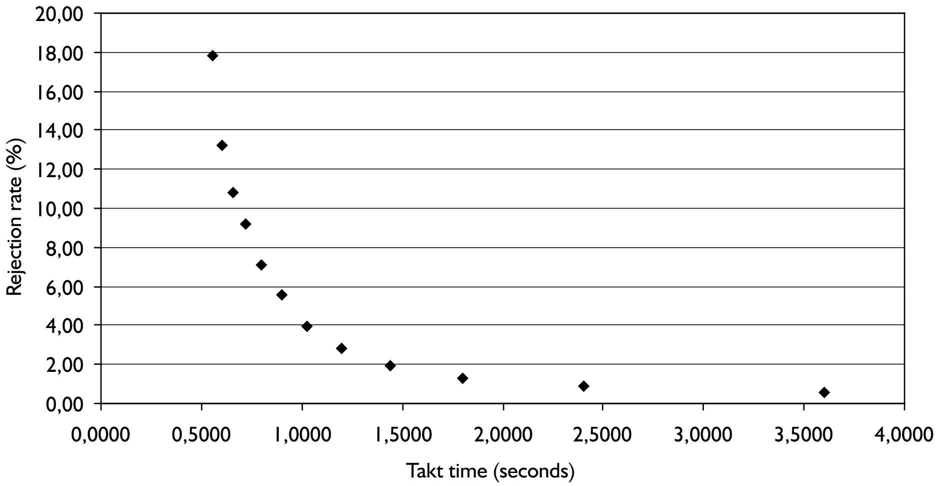

Figure 7 – Takt time *vs.* rejection rate for product 1 on the paster work station.

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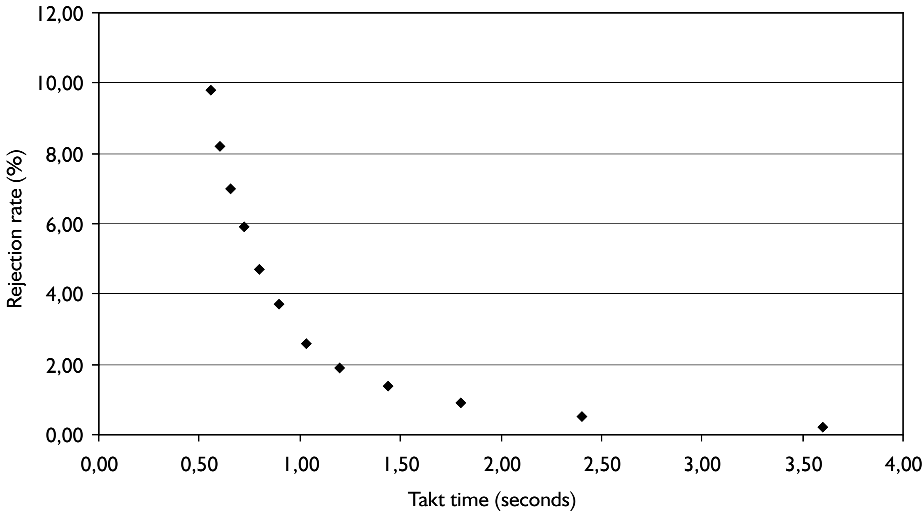

Figure 8 – Takt time *vs.* rejection rate for product 2 on the highlighting work station.

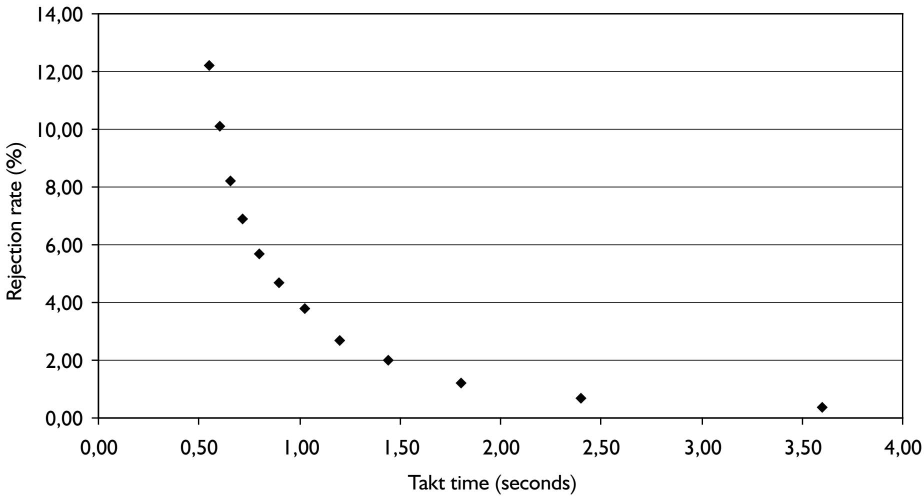

Figure 9 – Takt time *vs.* rejection rate for product 2 on the paster work station.

- **Product 2:** The effective takt time is equal to the cycle time (1.2 seconds) and the rejection level is high. As the work will be done in a line, the line effective takt time 2 will be the highest effective takt time of the work stations. Arguing as above, the effective takt time 2 of the highlighting work station will be the takt time equivalent to the 2% rejection rate, and the effective takt time 2 of the paster work station will be also the takt time equivalent to the 2% rejection rate. Therefore, based on interpolation of data from Figures 8 and 9, the effective takt time 2

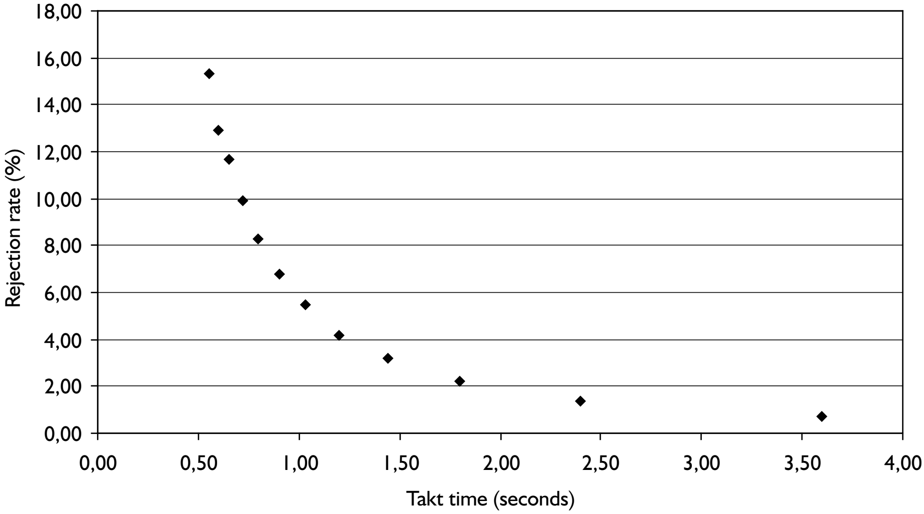

Figure 10 – Takt time *vs.* rejection rate for product 3 on the highlighting work station.

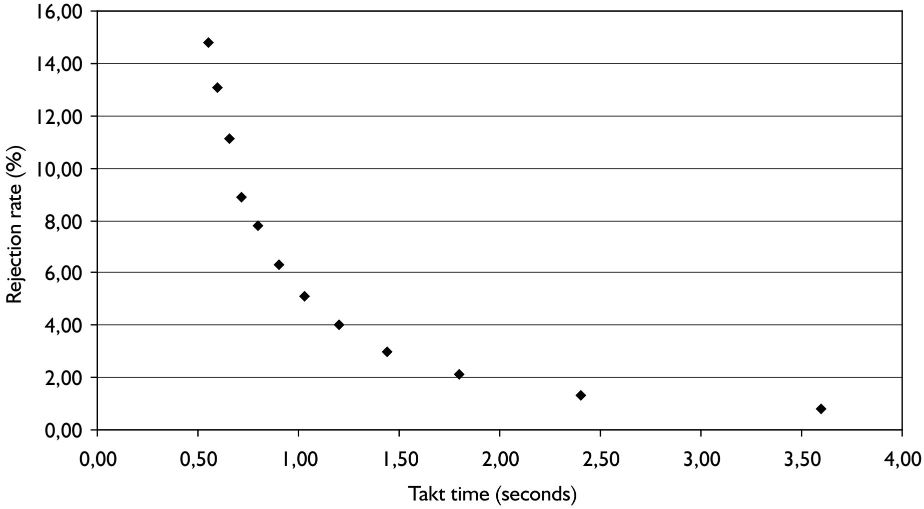

Figure 11 – Takt time *vs.* rejection rate for product 3 on the paster work station.

for highlighting and paster are respectively 1.18 seconds and 1.44 seconds. The effective takt time 2 for the line will be then 1.44 seconds (the highest one between them). This takt time is much greater than 0.9, which was the calculated takt time. In order to reach this takt time, an improvement in cycle time (capacity) and a drastic improvement in the process (aiming to reduce the rejection rate) will be needed.

- **Product 3:** The effective takt time is equal to the calculated takt time (2.1 seconds) and the rejection level is low (row 2 of Table 2). The effective takt time 2 for this product will be equal to the effective takt time of 2.1 seconds. In this case the demand will be fulfilled and the rejection rate can be reduced by means of six sigma/TQM efforts.

Conclusions

This paper has presented and applied a proposal for integrating materials flow, production control and quality control at the shop floor level. The proposal focuses on two important management functions: PC (choosing an adequate production control system and work flow that improves productivity and time) and QC (understanding that the reduction in rejection rate with subsequent efforts to improve quality is essential to the flow maintenance).

Many strategies have been proposed in the literature for improving manufacturing management. These strategies, which are based on principles, were not reviewed because they have different proposals in relation to the strategy proposed in this paper, the IME. However, we would like to mention the tenth (and last) principle of the responsive manufacturing strategy named QRM (Quick Response Manufacturing) proposed by (Suri, 1998): "The biggest obstacle to QRM is not technology, but "mind-set". Combat this through training. Next, engage in low-cost or no-cost lead time reductions. Leave big-ticket technological solutions for a later stage." This principle points out that some difficulties will always appear in implementing any strategy for improving manufacturing management: people do not want to change the way they do things but, on the other hand, human commitment is essential for reaching true improvements. Besides, the following message is universal: expensive technological changes must be postponed until cheaper priorities have already been implemented.

Focusing on the three principles of our proposal , the IME, it can be said that simplification of the materials flow is derived from Group Technology. So, this is not a new principle. Ashby's cybernetics law - "Only variety can destroy variety" - is the inspiration for our second principle, which is related to Production Control while Ashby's is a general law for the area of control by means of communication. Our third principle is the most original in terms of literature and it is based on a Brazilian proverb ("Haste makes waste"); i.e., things must be done rapidly, since this helps the reduction of leadtimes, which is prescribed in the strategy proposed by (Suri, 1998). However, he does not add an essential component: we must be fast only as far as velocity does not disrupt quality (our third principle).

The algorithm proposed in this paper contains an original numerical measure, "effective takt time 2". This measure is more complete than the definition of "effective takt time" that is present in the literature; it is worth to point out that it is exactly the effective takt time 2 concept that makes it possible to formally relate Production Control decisions (production pace) and the important Quality Control variable (rejection rate)..

The case study illustrates the application of the IME's three principles in the case of repetitive production systems. The widening of the IME's scope for semi-repetitive and non-repetitive systems will be a task for future research. Also, further study is required to determine whether it is better to have each processing unit controlled by the ideal PC system, or to have all processing units controlled by the same PC system.

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Biography

Flavio Cesar Faria Fernandes is a Associate Professor at the Federal University of São Carlos in Brazil since 1991. Now-a-days, he is supervising 5 PhD students and 2 MSc students. He has authored more than 40 papers on production planning and control, operations management and operations research, and refereed for several academic and professional journals. During 1998 he has been a visiting scholar in the School of Mechanical, Materials, Manufacturing Engineering and Management of the University of Nottingham in the UK. The principal current interests are about responsive manufacturing, operations management on shoes manufacturing and how to reduce the gap between theory and practice in the production planning and control field.

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Maurice Bonney was Professor of Production Management at the University of Nottingham from 1986 until he retired in 1996 and became an Emeritus Professor. He is still active in research. For some time he was Head of the Department of Manufacturing Engineering and Operations Management. He was President of the International Society for Inventory Research from 2000-2002. His research interests include production and inventory control, frameworks for production planning and control, integrated manufacturing systems and computer- aided tools for industrial engineering, including CAD. He is a founder director and part owner of two technology transfer companies: BYG Systems Ltd. and SAMMIE CAD Ltd. In 1994, the three founders of SAMMIE CAD Ltd. were awarded the Ergonomics Society´s Otto Edholm applications award. In 1998 the University of Linköping Institute of Technology in Sweden awarded him an honorary doctorate for his work in production control and ergonomics.

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