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FLEXIBLE AND RECONFIGURABLE MANUFACTURING AUTOMATION FOR MASS CUSTOMISATION

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Abstract: Mass Customisation, meant as an approach to product definition and conception that aims at a direct involvement of the consumer in all phases of its life cycle, implies making use of appropriate tools and technologies, especially in all crucial phases of manufacturing. In particular, the manufacturing systems adopted should exhibit the maximum level of integration and flexibility to cope with the extreme fragmentation of the production batches and with the very short response time that these new business model requires. A further enhancement to flexibility is re-configurability. The paper introduces these concepts and give an example for shoe mass customisation *Copyright © 2002 IFAC*

Keywords: Flexible Manufacturing Systems, .Mass Customization

1. INTRODUCTION

Mass customisation starts to become an important concept for today solution to improve sustainability and be more cost effective (Pine, 1993). Flexible manufacturing has been associated with lower lot sizes and longer equipment life with more rapidly product changes and variation. Reconfigurable manufacturing is the next step to bring the full potential to mass customisation: we can say that mass customisation is also pushing for customised manufacturing (Koren, *et al.*, 1999).

As the definition of mass customisation recalls, aiming at offering the consumers goods and services that are more and more tailored on their specific needs, tastes and wishes implies having the capability of conjugating the efficiency and the scale economy of mass production with the possibility of manufacturing unit or quasi – unit lots of very diversified and personalised products; a very strenuous challenge for the entire company organisation, whose procedures and management approaches then require a thorough revision, especially in the manufacturing area.

The traditional approach tuned on the production of relatively large batches of similar products with a minimum number of changes and modifications, a low number of machine set-ups and a low cost impact of the tools and fixtures necessary for the production, evolves in a much more frantic way of working in which machine set – ups can occur for every single lot and tools, when necessary on a one to one basis, cannot find any economical justification.

This is certainly true also for shoe production; although footwear manufacturing is more and more confronted with a progressive reduction in the size of the production lots, with a variability of styles that tends to overstress the traditional work organisation and with a demand for reducing as much as possible delivery times, it did not yet approach the levels of flexibility and quick response that the production of mass customised products would require. But, since a noticeable demand for such kind of goods is getting evident also among shoe consumers, footwear companies will soon have to get confronted with the kind of technical challenges that were mentioned before.

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1.1 Implications of mass customisation on shoe manufacturing

To understand the implication of mass customisation on shoe manufacturing, we should try to find a more accurate definition for this concept of customisation when applied to footwear. If customisation, in general terms, means introducing in the product a certain number of personalised features that somehow reflect the consumers' desires, shoe customisation can be thought of in several levels; we can in fact think of:

- Design customisation, for which only some aspects related to colour and material combinations, or small details and decorations can be selected and configured on the specific wishes of the consumers; this first level of customisation has a limited impact on the organisation of production and on the required technologies, yet enhancing the complexity of the whole process thus requiring very efficient planning and management tools.
- Size and fit customisation**,** that, in addition to the requirements of the previous level, also implies building the shoe on the specific dimensions and features of the feet of the individual consumer; this second level can be further detailed as
  - Best fit approach**,** for which size and fit customisation is achieved by looking for the last – style combination that is the best **approximation** of the consumer's feet sizes and desires
  - Custom made approach**,** which is the ultimate level of customisation for which the shoe is actually designed and built **exactly** on the dimensional (and other) requirements of the consumers.

Both these two last levels of shoe customisation have a more and more significative impacts on manufacturing; the most complex case, that we will adopt to better understand the ultimate implications of customisation on shoe manufacturing, is the one related to producing custom made shoes. We should now remember how a shoe is made and what are its "building components".

As it is seen in the picture above, to manufacture a shoe we need first of all a **last**, then a certain number of components: the **upper**, that is the skin (in leather or synthetic materials or in a combination of them) of the shoe (the upper itself is made of a variety of parts such as the linings, counters, toepuffs, stiffeners), the **insole** (sometimes in the form of conformed foot bed) , the **sole** (in leather or plastic) and the **heel**. In a strictly customised shoe the majority of these components (if not all of them) depend on the specific foot dimensions of the individual costumer.

When we think of a custom made shoe the situation is completely different; while retaining a "modular" approach for the selection of the desired style (it is unlikely that each single consumer will ever become a designer of his own shoes), all the components of the shoe do in fact comply with a different criterion that we may call "parametricity": the general design of the shoe (that can be generated in a sort of "neutral" size) must be adapted case by case according to well defined consumer parameters (length of the foot, girth length, and whatever else is significative). The negative implication is that the manufacturing unit cannot produce until customers' orders are collected (an 180 degree deviation from a made for stock to a made to order manufacturing approach).

Producing custom shoes means then aiming at a situation where manufacturing lots are strictly unit ones (each customer is different end even left and right shoes can be different); so, all tools of any kind that are necessary to manufacture represent obstacles: time - wise since their production significantly affects the delivery time for the shoes and cost – wise since their costs directly contribute to the final cost of the produced shoes.

1.2 Manufacturing in Mass Customisation

As stated above, to obtain the competitive advantages promised by the Mass Customisation paradigm, both the organizational structure and the productive process must be updated (Carrie, 1999). The emerging tendency by capital goods producer to became service provider rather than product provider –according to the *Global Service* philosophy - helps to make the whole scenario more homogeneous inside the Mass Customisation context and its related requirements. Also for manufacturing companies, in fact, some of the themes related to customized service providing become actual problems. Manufacturing companies, then, need to be "customer oriented" rather than "product oriented", consequently changing its own organizational structure. There is an identifiable trend to ask for manufacturing services (rather than production units) that could be rented only for the term of use; this is true above all for SMEs, as they don't have great financial resources at their disposal. Together with the development of systems able to evolve during its own life cycle and to adapt to market requirements (described above), renting the desired configuration of such a manufacturing system may be a "financial" instrument to Mass Customization. A number of

different, new strategies are developing to deal with these market developments that require a market layout redesign. On the system producer side, the manufacturer of the machinery could retain ownership and lease "production hours" or "products per month", taking responsibility for operation, programming, service, maintenance, etc. The customer (a material goods vendor), would pay this service. As an alternative, a "System Integrator" might act as a "Technology Broker", working as an interface and arbitrator between a company that needs a given productive capacity and a group of functionalities and one producers of modular macro-components of the production unit (Bal et alii, 2000). This actor, probably supported by a finance and leasing company, would be responsible for the selection of the modules (that could be ordered by a sort of internet based common and transectorial market), their customisation for the required process and integration. This new actor could rent a customized production capacity (related to a peculiar process) to the end user together with operation and maintenance services and, after the term in use, could disassemble it into basic "building blocks" and reuse them to assemble a new production capacity fitting a new end user requirements.
Maintenance and reliability (that are expensive and time consuming) become critical aspects in these evolutionary layout. Maintenance, in fact, is part of the service provided, so that the provider is interested in minimizing it. Equipment must then be designed for maintenance. Modularity and reconfigurability in manufacturing systems and system components must be considered as key enabler for such a new market layout (Wiendhal et alii, 1999). It must be noticed that in such a scheme the system provider becomes a process provider. This is coherent with the Mass Customisation paradigm, in which, as previously described, the emphasis must be laid on the process and its life cycle rather than on the product: many products are realized inside one process, and each process lasts longer then the product realized inside it. The kind of update in the organizational structure of the enterprise (suitable for the described market layout change) can be considered as a part of the Extended Enterprise approach (Boer and Jovane, 1996) that seems to be a promising paradigm that allows enterprises, and in particular SMEs, to cope with the dynamic nature of current global market and to compete with bigger organisations (Childe, 1998).

2. ANALYSIS OF FLEXIBILITY AND RECONFIGURABILITY

An analytical approach that may help to decide the kind of manufacturing system to be used in dynamic contexts is presented by Urbani et al. (2001). It is referred in particular to mechanical machining.
When we need to produce a given part, the best solution from the point of view of cost, time and quality must be certainly looked for among dedicated solutions. A dedicated solution can be optimal according to the desired goals. When introducing flexibility to cope with wide mixes and/or volume fluctuations, optimality about each of these goals is lost. By using a reconfigurability-oriented approach it is possible to partially achieve the advantages of both dedicated and flexible solutions, that is both optimality and the ability to cope with varying situations. Obviously this is not always the best choice, but there may be conditions of mix and volumes (Urbani, *et al.*, 2001) in which it can be an effective solution.
Such an approach, anyway, cannot be considered completely new, as kinds of reconfigurability have often been considered in many kinds of systems. Scalability, in fact, can be considered as a reconfigurability-oriented property. This means that reconfigurability must be considered as one of the abilities which a system can be equipped with.

In order to take system reconfigurability into consideration, system life cycle must be divided into successive production periods T. Each one of these periods corresponds to a known *productive objective* (mix and volumes) which is realized in one *configuratio*n. As reconfigurability may try to combine the effectiveness of dedicated solutions with the ability to manage variable demands, two system concerning aspects must be taken into consideration to get reconfigurability measures:

- The <u>efforts</u> to modify the system's and the system's components structure.
- The <u>efficiency</u> in functionality implementation.

The easier to modify the system and its components the more reconfigurable the system itself. Being able to cope with demand changes through flexibility is an optimum under this point of view. In such a situation, in fact, no modifications are needed (we are not taking software modifications into consideration). But in order to be able to cope with expected and unexpected demand changes a flexible system must use very wide functionalities, which could also result to be underused. Furthermore, a great flexibility is a very expensive feature. Then, to effectively analyse the ability to cope with wide demand fluctuations the efficiency in the implementation of requested functionalities must also be considered.

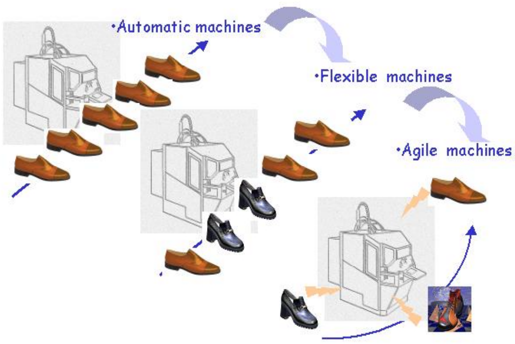
After the identification of the system components to be analysed (in an automated machining system, for example, the system components can be divided in 5 main components: machines, fixtures and pallets, tools, tools and material handling system, warehouses) reconfigurability analysis can be applied to each of these components to get to the analysis of the whole system. Each component can be associated with a general functionality that it has to realize. Each functionality (characterized by its own technological attributes) can be decomposed into sub-functionalities. As previously stated, a key-enabler for reconfigurability is modularity of the components. The modules (defined by the granularity implemented) and the relationship among modules which are used to work a mix during a period T define the configuration corresponding to period T.

Each module is made up of one or more (functional) elements.

By defining the correspondence between functionalities and the modules which implement them, it is possible to find general, high level reconfigurability measures.

3. FLEXIBILITY TO RECONFIGURABILITY: EXAMPLE OF EVOLUTION IN SHOE MACHINERY

Shoe machinery are used in all phases of production and they have undergone, since their first appearance at the beginning of the century, a significative evolution. From simple mechanical devices electrically powered, they first turned into complex machines, with mechanical, pneumatic and hydraulic components and then, nowadays, into very complicated mechatronic systems. It is in fact today very difficult to find automatic shoe machines without a robust mechanical design, a relevant electronic presence and a great deal of computers to plan, control and supervise their operations. By observing how these machines evolved we can highlight a definite trend that has transformed these devices from automatic to flexible and which will then have to turn them into agile equipment.



3.1 Automatic machines

We may assume this to be the first level of automation and the first one to appear historically; automatic machines can be (manually) programmed and they can execute their tasks in an autonomous way, albeit requiring a large amount of reprogramming if they have to switch from one article to be produced to the other; sometimes it is even necessary to reconfigure them to change the kind of production. Reprogramming / reconfiguring time is high and can be as big as the whole processing time. So they are suitable only for large scale production with a very low number of variants. They can also be seen in modern production systems for the execution of simple repetitive tasks which are not so sensitive to product changes. This kind of machines could not be easily integrated in a complex production system and are adopted for high volume productions with a limited number of variants.

3.1 Flexible machines

Flexible machines added a new dimension to automation; as long as production meant manufacturing big lots of everlasting products in a relatively stable market, automatic machines played a big role in assisting human workers in their job and, mainly, in increasing the productivity of the manufacturing units; but when the situation changed, with lots becoming smaller and smaller and with an explosion in the number of articles to be produced, automation alone was not enough. So shoe machines evolved, and they are still evolving, into flexible units; a flexible machine can rapidly switch from a specific article to other and can rapidly adapt to producing lots of very different size. Reprogramming is very fast, set-up times are then reduced to a minimum (machine adjustments related to changing the size of the shoe are handled automatically) as a minimum time is needed to "reconfigure" the machine (or a part of it) in changing from one shoe style to the other. These machines are ideal for integration in complex production systems; normally they are equipped with state of the art Numerical Control boards that can be connected to the shop floor data backbone in order to receive in real time information on what to produce and how (part-programs to be executed for a given shoe style)

3.3 Agile machines

Future demands, like those ones related to mass customisation, call for a further step forward; flexibility will have to be conjugated with other capabilities so that machines of the future generation will be developed along these three technological vectors:

- maximum flexibility, up to the design target of completely eliminating every set-up in changing from one style to other and getting rid of all the tooling specifically needed for each given model
- enhanced versatility, meaning by that the possibility of executing with a single machine and by using the appropriate effectors , more than a single operation, thus replacing, in the manufacturing cycle, many machines at the same time
- self adaptation, in order to be able to respond dynamically to changes in style or size and, more than that, to automatically adapt to the "real world" situation (a data transfer line that drops, a part that arrives at the given manufacturing station badly assembled or not precisely positioned). This capability will make the machine more "autonomous" so that it can execute its task also in a stand alone situation (loss or no communication with the shop floor information system) and is achieved by equipping it with active sensors (from cameras

to other kinds of devices) that can sense and monitor the part of the manufacturing world the machine is responsible for. This self adaptation capabilities might also lead to machines capable of diagnosing their defects and, to a certain extent, to self repair them.

4. EXPERIMENTING FOR FLEXIBILITY-RECONFIGURABILITY: FROM THE PROJECT SPI-6 TO EUROSHOE

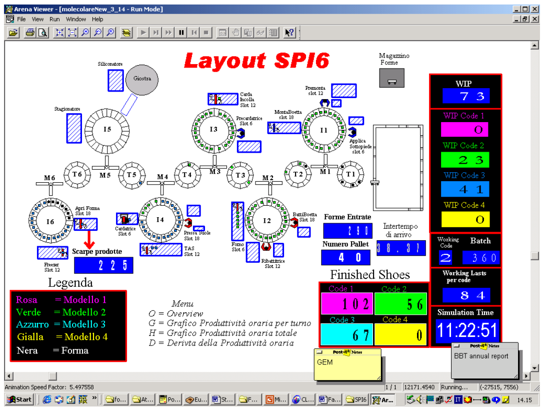
In the shoe sector we have been experimenting with the new concepts described above in the main projects SPI-6 and EUROShoE.

4.1 The SPI-6 Project

The project was part of structured research program launched in 1994 by the Italian Ministry of Scientific Research to foster the development of Innovative Manufacturing Systems (SPI – Sistemi di Produzione Innovativi) in a variety of industrial sectors, including the shoe one (Project Nr. SPI 6). In the project specifications drafted by the Ministry, the technical emphasis was on aspects such as the integration between product design and manufacturing, the systemic approach and the automation of some of the most important phases of footwear manufacturing. The research contract was eventually assigned in November 1997 to a consortium formed by the National Research Council of Italy on one side and five among the most important shoe machinery producers on the other (Consorzio Sintesi).

The project had a budget of 5.96 million EURO and it involved more than fifteen partners, including research institutes, technology suppliers and, of course, footwear companies. During the initial phases of the research work, all the specified technical contents were developed; they spanned from the area of last standardisation and manufacturing, to studying new techniques (like the adoption of Virtual Reality) the ease the access of shoe stylists and designers to the use of CAD systems, to developing solutions for the texture analysis of the leather skins to be used to produce uppers, to conceiving and implementing a fully automated conveyor system aimed at serving the making department with dispatching the work in progress to the relevant station in a fully automatic manner and under the control of a Computer System.

In the last year and a half (the project was completed at the beginning of May of year 2001) single machines and specific equipments were built and tested and then, in the last nine months, they were assembled as an integrated manufacturing plant that was extensively used during the final validation phase. This phase involved the production of more than 1500 pairs of shoes of different styles and construction typologies. During this final phase, the plant was run as a "real" shoe factory with an integrated manufacturing cycle that, for some of the styles produced, included all the three typical phases of shoe production: cutting of the leather and synthetic components of the upper, stitching the various components to form the complete uppers and then assembling, on the last , the upper with other shoe components (the insole, the sole and the heels) in the final making phase. This first hand manufacturing experience gave the possibility of analysing in a semi – productive environment the aspects related to the integration of the various system modules in one complete system and of experimenting the response of the system itself, in terms of flexibility, to handling very diversified productions and unit lots.



The Spi-6 Integrated Pilot Plan

The plant is designed in order to take maximum advantage of **integration** for added flexibility in term of lot size, responsiveness, cost reduction. There is a:

- **Vertical integration** between design, process programming, process planning and then manufacturing and a
- **Horizontal integration** between the different stations and modules of the shop floor; this is organised in three main departments (or stations): cutting, stitching and making.

The experimental results show that the flexibility is confirmed in terms of lot size, responsiveness to design change and to throughput time as well as cost reduction. Just as an example a single pair of woman shoes (classic type) can be modified in some small part and then directly manufactured in less than an hour. The modification starts at the CAD station and then automatically the corresponding manufacturing and assembly cycles are generated, the production plan is modified to give priority to the single pair of shoe, the corresponding form (or last) is called from the automatic store and is fed through the integrated plant where the single machines use the right CAM program to do the single operations necessary to complete the shoe.

4.2 The EUROShoE project

EUROShoE is a research project aimed at a dramatic renovation of the concept of the shoe as a product and of its production, based on the transformation of the first from a mass produced good to a mass customised one; this product evolution goes in

parallel with a transformation of the footwear company into an extended and agile enterprise (Boer, *et al.*, 1999) capable of handling the complexity that such a change in the nature of the product implies and of mastering the new challenges deriving from a direct involvement of the consumer in the design and manufacturing process of the shoe he is going to buy. Such a radical change in the product nature forces a complete revision of the processes that support the various phases of the product life cycle (design, production, sale and distribution, use, dismissal and recycling) in a systemic view that is developed within the EUROShoE project according to the model of the product – processes matrix leading to a research effort that encompasses the development, for each of them, of all the relevant critical technologies. This total and global rethinking of the footwear business needs large resources and the EUROShoE project is therefore an ambitious and large research initiative involving all the actors of the value added chain (EUROShoE, 2001).
The approach is on one side looking at the "shoe system" and on the other side developing the necessary methodologies and technologies needed at every step of the value added chain. Moreover the entire project aims at a web orientated transformation of the business and operational mechanisms of traditional enterprises like footwear companies are, thus helping a typical "old economy" manufacturing business to evolve into a "new economy" one but without loosing his ground in manufacturing.

In order to tackle such a complex task, a consortium of companies at the European level must be formed; this is thought to be necessary for two distinct reasons: first the know how which is deemed necessary to achieve the research goals cannot be found in one single country, but it must be gathered from private companies, universities and research centres, both with general and specific expertise, based in different countries. The second reason is related to the aim of developing solutions with a general validity for shoemaking companies from all the major European footwear producing countries, so that the results will contribute to a general improvement of the sector. For this reason the contribution of shoemakers from different countries will be gathered.
The project responds, within the European Commission 5th Framework Program to the specific program "Competitive and Sustainable Growth" – Call Growth 2000, and to the key action Innovative Products, Processes and Organisation. The problems which the project addresses are of great relevance for the sector, which has been very attentively monitoring them; this allows to forecast a relatively short time for the exploitation of the results.

5. CONCLUSIONS

The concepts of flexibility, agility, reconfigurability related to mass customisation have been introduced and the important role of the manufacturing aspect has been described.
An approach to reconfigurability design has been also described and the shoe sector has been used as example. Two main projects is this area have been also introduced to show how it is possible to evolve from a flexible production plant to an extended enterprise for shoe mass customisation.

6. ACKNOLEDGMENTS

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