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# A new system architecture compared with conventional production system architectures

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A new concept of manufacturing system architecture is proposed in order to improve the reaction of the firms to the growing requests of productivity and flexibility of the market of metal components for the automotive industry. The new system architecture allows firms to produce, in a profitable way, a mix of different families of parts required in medium–large volumes. This paper proposes a description of the system architecture pointing out its advantages and drawbacks in terms of productivity and flexibility. In addition the proposed system architecture is compared with rigid transfer lines and parallel machines flexible manufacturing systems on the basis of discounted cash flow indicators. Rigid and flexible systems are compared taking as a reference a real case. The influence of the variability of products and volumes on the profitability of the different system architectures is also investigated in this paper.

## 1. Market trends

The global market of metal components for the automotive industry is undergoing significant changes. The fierce market competition leads firms to increase the flexibility of their facilities in order to react to the frequent market changes (Matta and Tolio 1997, Gunasekaran 1998, Koren *et al.* 1998, 1999). The reason for this change in turn is motivated by the fact that automotive suppliers tend to increase the range of products to attract the consumer, launch new models of car and decrease the time to market; i.e. the more attractive products in shorter intervals they propose in the market, the more competitive they are. Each component manufacturer tends to produce well-defined types of products (e.g. outlet manifolds) that are supplied to different car manufacturers, therefore the market is composed of fewer and fewer focused suppliers. The whole market of final goods is subject to uncertainty: each single final product can be a success or a failure and the same is true for components that constitute the product. Given the fact that stock reduction and JIT policies are normally adopted, the producer of components must follow, even in the short term, the fluctuation in the demand. Also the weak contractual power of producers of components reduces the profit per part. Car component suppliers suffer from this trend. They have to face frequent changes in product demand, changes in mix, modifications on existing products and introduction of new products. In this situation to select the best production system in terms of profitability is not an easy task.

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Existing production systems do not match the above market trends. Traditionally rigid transfer lines (RTL) have been adopted for the production of a small family of part types (one or few part types) required by the market in high volumes (Koren *et al.* 1998). Because RTL scalability is low, RTLs are normally dimensioned to reach from the beginning the maximum market demand the firm forecasts to satisfy in the future. But in many situations RTLs do not operate at full capacity due to the lack of demand [analysed RTL operating in the sector of automotive components were saturated 53% on average (Matta and Tolio 1997)]. In this case RTL profitability is very low because the potential capacity of the system is not exploited. On the other hand, flexible manufacturing systems (FMS) and parallel machine–FMS (PM–FMS) have been adopted for the production of a large mix of parts to be produced in small quantities (Grieco *et al.* 1995, Hutchinson and Sinha 1989). FMSs are conceived to react to most of the possible changes of the market, therefore their flexibility may be too large and expensive for the needs of components for the automotive industry (Sethi and Sethi 1990). In many cases, car component suppliers partially exploit the flexibility offered by these systems, given the fact that it is rare that their part mix changes completely. Investment to acquire FMS is very high and it considerably affects the cost per part unit produced.

It is important to measure the benefits due to the flexibility in order to know the situations in which rigid or flexible systems should be used. Previous work on the comparison between rigid and flexible systems has been performed by Hutchinson (1976). Hutchinson compares a rigid transfer line and a flexible line on the basis of their net present value considering the uncertainty related to the market demand.

This paper proposes a new system architecture that has the potential to be more profitable than RTL and PM–FMS for the production of parts with a defined range of changes in mix, features and volumes. System architectures are compared in different scenarios that point out the systems performance in different situations of production mix and market uncertainty. The paper is organized as follows: section 2 contains a description of the new system architecture and its innovative concepts. The proposed system architecture is then compared with RTL and PM–FMS in section 3 on the basis of their net present cost defined below, and conclusions are drawn in section 4.

## 2. Description of the system

The main goal of the new architecture called Mod–Flex–Prod (MFP) is to provide a balance between productivity, intended as profitability, and flexibility. MFP is an automated and integrated system in which parts can be processed either by a set of modular NC machines organized as an automated flow line, or by single machines, organized as a PM–FMS. The system can be run as a set of short mini-lines, each one can work different products. For instance, the system in figure 1 composed of six machines works with two mini-lines of three machines: part types A and D are machined in the first mini-line and part B in the second mini-line in the first shift. In the following shift the same system is set in a mini-line of three machines to produce products A and D, a mini-line of two machines to produce product B and a standalone machine to produce product C.

Raw parts are automatically loaded into the system by a gantry robot that takes parts from the input buffer and moves them (the robot is mounted on the part carrier) to the assigned mini-line where they are machined. Each part program is divided into different portions assigned to the machines that compose a mini-line.

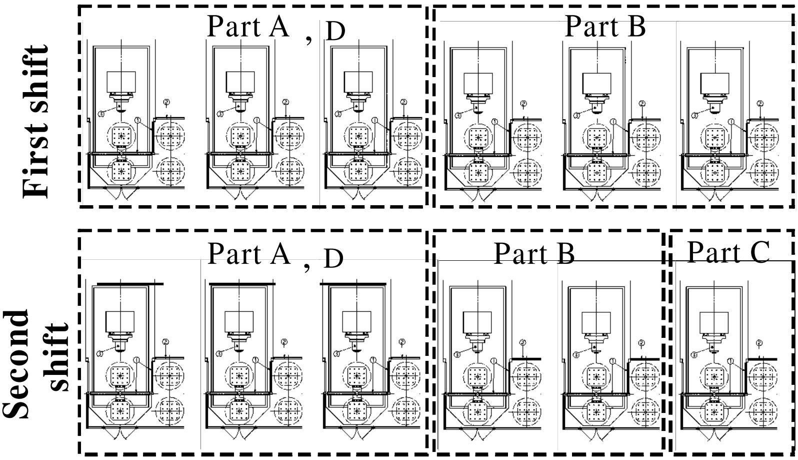


Figure 1. Example of re-configuration of the system.

Each machine performs only a sub-set of operations of the whole part program. The gantry robot is able to clamp part on hydraulic fixtures and unload parts after they complete their processing cycle in the mini-line. Parts are then moved by the part carrier to the output buffer of finished parts and leave the system. The system is completely unmanned except for the loading of raw parts into the input buffer and the removing of finished parts from the output buffer: one or more operators place manually raw parts in the input buffer and remove finished parts from the output buffer. As in FMS and PM–FMS it is possible to share tools with a tool carrier, which moves them from the central tool storage to the machines, and to manage part and tool flow by means of the system supervisor that guarantees system efficiency and availability during the operating time.

Profitability and flexibility of the new system architecture are now discussed below. Investment cost of machines is remarkably reduced in comparison with PM–FMS. Machines are at least 50% smaller than traditional machining centres, whose envelope covers usually a cube ranging from 600 to 1200 mm, with critical consequences on their costs. Therefore, machine basements could be advantageously obtained with different processes (e.g. casting), feed drives can be reduced in their length and linear motors with low payloads can be profitably adopted (due to low forces and total length of permanent magnets) for the fast movement of axes. In addition, fixtures are smaller in order to match with the reduced envelope of machines ($350 \div 400$ mm). This feature reduces only unneeded machine flexibility as most of the parts in the automotive industry fit with the working area of MFP machines. Therefore, both machines and fixtures reduce the investment cost of the system improving its profitability.

Moreover, investment in tools is significantly reduced in comparison with FMS. Each machine executes only a portion of the whole part program; this fact reduces the number of tools in the mini-line because the same operation is normally performed on the same machine. In such a way, assuming that each operation requires a different tool, it is not necessary to load the same types of tools on different machines and the total number of copies of tools in the system can be reduced. This in turn reduces the required tool magazine capacity.

Finally, the new system architecture preserves different types of customized flexibility to react to changes in product demand and mix ratio, changes in product features and changes in product ratio. As for the short-term demand fluctuations, it is possible for the user to follow the market simply by tuning mini-lines length by means of rapid system re-configurations which imply the time for moving tools to the machines and for substituting fixtures (a system re-configuration can be completed in less than 15 min). The decision on how many machines compose a mini-line can be taken at a loading management level. Variations on demand in medium- and long-term can be accommodated by expanding the system with new machines, fixtures, part and tool carriers. Modifications on products can be simply accommodated by adapting only fixtures and part programs if product dimensions do not exceed the allowable sizes.

## 3. Comparison with alternative production systems

### 3.1. *Assumptions*

In order to compare different manufacturing system architectures it is necessary to define discriminating indicators. Productivity is defined as the amount of output obtained for one unit of input. We consider the production rate of the system as the output and the total cost of the system as the input. It is rather difficult to increase productivity of manufacturing systems as a specific action that can increase the production rate of a system is normally balanced by the effort required. Actions that can improve system productivity should reduce the total costs (reduction of machines and fixtures cost, reduction of adaptation cost, etc.) without reducing the production rate, or should increase the production rate (shorter system set-up times, reduction of unproductive times, improvement of system availability, etc.) without increasing costs. An indicator of the costs related to an investment is the net present cost ($NPC$), defined as the overall cost of the system during its life cycle (Matta and Tolio 1997):

$$NPC = \sum_{t=1}^{T} \frac{I_t}{(1+k)^t} + (1 - tax) \sum_{t=1}^{T} \frac{\mathbf{c} \cdot \mathbf{x}_t}{(1+k)^t} - \sum_{t=1}^{T} \frac{D_t \cdot tax}{(1+k)^t} - \frac{RV_T \cdot (1 - tax)}{(1+k)^T}$$

with

| | |
|---|---|
| $c$ | vector of operating costs per part, |
| $x_t$ | vector of number of pieces produced in the period $t$, |
| $t$ | time period, $t = 1, \ldots, T$, |
| $D_t$ | depreciation cost of investment in the period $t$, |
| $I_t$ | investment in the period $t$, |
| $k$ | risk rate, |
| tax | tax rate, |
| $RV_T$ | residual value of the investment at period $T$. |

Our goal in this section is to provide an economical comparison of the new system architecture, called MFP, with rigid and flexible systems, i.e. RTLs and parallel machines–FMSs, respectively. In order to compare the systems, we have estimated the investment and operating costs incurred by a hypothetical firm operating as supplier of metal components in the market of automotive industry. All the measured costs are related to the introduction of a set of products into a new production system (which can be an RTL, or an MFP or a PM–FMS) that we assume the firm has to acquire because additional machine capacity is necessary in its shop floor. *NPC*s of the three systems architectures have been evaluated and differences among them are pointed out.

It is worthwhile noting that all the data used in the comparison have been collected from a real case. In particular we have analysed a set of parts of a big supplier of components for the automotive industry collecting both the technical data (operations, processing times, tools, etc.) and the economical data (demand, life cycle, modifications cost, operating costs, etc.) related to the selected mix of parts and that are necessary for the analysis.

The comparison is developed into four different scenarios with an increasing level of complexity. In particular, two different key issues are considered in the comparison: the production mix and the uncertainty of the market demand. The production mix, which we assume the firm will produce in the planned time horizon, is a relevant variable that must be taken into account when the production system is selected, as it deeply affects the needed level of flexibility of the whole system. We consider two extreme cases to point out the main differences of the three types of production systems: a very small production mix composed of only one part type and a production mix of eight part types. The second key issue is the uncertainty on the volumes that the market can require in the future. Again two extreme cases are considered. In the first case it is assumed that the firm knows exactly the levels of demand of its production mix; in the second case the uncertainty related to the volumes is considered. Four different scenarios are obtained by the combination of the above extreme cases; the scenarios have the following common assumptions.

The length of the life cycle of each product is known by the firm before the introduction of products in the new system. Indeed it is common practice that contract negotiation with customers fixes a minimum period of product supply. We assume that the total length of the product life cycle is 6 years.

- Each product undergoes some modifications on its features during the life cycle. However, the consequences of modifications have a different impact on rigid systems and flexible systems.
- For each product of the mix it is assumed that the peak value of the market demand cannot be greater than a maximum value known to the firm. It is frequent that contract negotiation between supplier and customer limits the demand variability defining some threshold values. In the automotive industry, customers must often respect a maximum level of demand. We denote with $CV$ this maximum contract value.
- Backlogging of demand is not considered. Given the low contractual power and the high penalties, the firm must always satisfy their customers and cannot be in stock-out. Also, for the sake of simplicity, we assume that the firm cannot outsource any product to external third suppliers. Therefore, each system must be dimensioned on the basis of the $CV$ of each product.
- The residual value of the investment at the end of the planned time horizon is equal to 40% of the initial investment for MFP and PM–FMS systems. On the other hand, RTLs have no residual value because of the specificity of the machines that are designed to perform operations on a specific part type.
- Excess capacity in PM–FMS and MFP is partially used to manufacture other products of the firm and therefore it is not included in machine investment

cost. This is motivated by the fact that the flexibility of MFP and PM–FMS allows the exploitation of the additional spindle availability that is not used by the production mix. However, it is not practically possible to use all the excess capacity. Therefore, a residual capacity saturation, denoted with *RCS*, is defined to represent the percentage of excess capacity of the analysed production systems that is allocated to other products. Note that the *RCS* of RTL is equal to 0% because of the rigidity of the machines.

In order to estimate the *NPC* of the various production systems, all the costs faced by the firm to produce the real production mix are evaluated. In particular, investment takes into account machines (control system is included), part handling system (pallets, fixtures, buffers, part and pallet carriers, load/unload stations), tool handling system (tools, central tool storage and tool carrier) and system supervisor. Operating costs include labour, tool wear (differentiated for milling, drilling and boring), maintenance, power consumption and cost due to modifications on part features. The number of parts produced and sold in the planned time horizon is the same for each production system, therefore the system with lowest *NPC* is the best system in terms of productivity.

### 3.2. *Scenario A: single product, no uncertainty in market demand*

The first scenario analysed is the simplest one because the production mix is composed of only one product (one of the eight products of the real case) and the firm knows exactly the constant volume that the market will require in the future. The product is a cast iron component that requires 24 different operations in order to become a finished part (quality control is not considered); the number of tools necessary to machine the part is equal to 14 and two working positions are necessary to machine the part in general purpose CNC machines. In particular the PM–FMS fixture contains parts in both the working conditions and nine parts are mounted for each position; on the other hand fixtures of RTL and MFP mount only one part.

RTL, MFP and PM–FMS are dimensioned on the basis of the *CV* of the product. Because uncertainty is not considered in this scenario, *CV* corresponds to the effective volumes required by the customers in the planned time horizon. For simplicity it is assumed that the market requires the product with the same quantities during the whole life cycle of the product.

In figure 2(a) the *NPC* for each analysed system is shown as a function of *CV* (expressed as number of units per day). Because machines cannot be dimensioned to satisfy perfectly the market demand without any capacity surplus, the *RCS* must be considered also in this scenario; in particular the graph is obtained assuming that the *RCS* of flexible systems is equal to 50%. The graph confirms that flexible systems are more productive than rigid systems for low volumes of demand. Note also that in this case the *NPC* of MFP is always lower than that of PM–FMS. As *CV* increases, the difference in terms of *NPC* between flexible and rigid systems decreases until the break-even point, defined in this paper as the point in which two systems have the same *NPC*, is reached. In particular, the break-even point (or *BEP*) is $\sim 285$ for RTL versus MFP and 252 for RTL versus PM–FMS. Therefore if, e.g. *CV* is equal to *BEP* of RTL versus MFP, it is the same from an economic point of view and with the above assumptions to select a RTL or a MFP for the production of the part type. For daily volumes greater than the *BEP*, RTL is clearly more productive than flexible systems. *BEP* of RTL versus MFP as a function of *RCS* is shown in

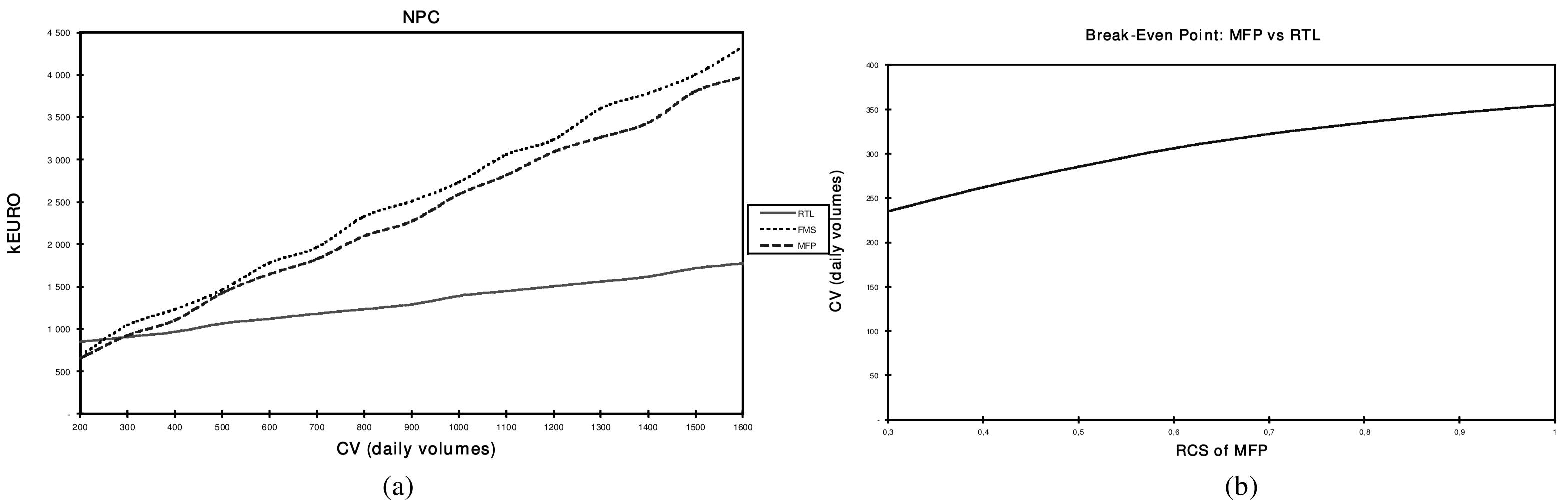


Figure 2. (a) Scenario A: *NPC*s of RTL, MFP and PM–FMS as a function of *CV*. (b) Scenario A: *BEP*s MFP versus RTL as a function of RCS.

figure 2(b); the function is obviously increasing in *RCS*, as the portion of the investment cost (exploited by other products), which is not considered in the *NPC* calculation, increases with *RCS*, and is limited between the values 235 and 355 for the analysed product.

### 3.3. *Scenario B: single product, uncertainty in market demand*

This scenario is similar to scenario A. The difference is that uncertainty of the market demand is now considered. That is, the firm knows the product and the length of its life cycle but it does not know the volumes that the market will require in the future. However, the contract negotiation forces the firm to dimension the system on the basis of the product *CV*, even if the future demand will be probably lower than this value.

Investment costs of each system depend on the product *CV* while operating costs depend on the quantities that are effectively produced by each system. Therefore, operating costs are related to the real volumes required by the market in the planned time horizon. In order to have an estimate of the expected value of the *NPC*, the quantities required by the market have been randomly generated from a distribution estimated on the basis of a real set of products. Estimates of expected values of *NPC* of the various systems are reported in table 1 for different values of *CV* and *RCS*.

It results that rigid systems are more productive than flexible systems when the production mix is limited and *CV* is medium–high, even if the uncertainty on the level of demand is considered. However, for low values of *CV* flexible systems are better than RTL. Note that *BEP* of RTL versus flexible systems is $\sim$ 500 parts/day when *RCS* of PM–FMS and MFP is 50% (see figure 3). Also, if *NPC*s of the different systems are compared with those of scenario A [see figure 2(a)], it can be noticed that the difference of *NPC* functions between flexible and rigid systems decreases when uncertainty is considered. That is, the advantages due to flexibility increase in scenario D where the risk is taken into account.

### 3.4. *Scenario C: mix of products, no uncertainty in market demand*

A real part mix of eight components has been considered for the evaluation of the *NPC* of the different system architectures. Six components of the mix are in cast iron while the other two are in aluminium. On average parts require 18 operations performed by 14 different tools in order to become finished products, the average tool contact time per operation is 17.6 s and the part envelope is lower than 400 mm. The production mix represents products required in low, medium and high volumes. Real

| $CV = 400$ parts/day | | | | $CV = 800$ parts/day | | | |
|---|---|---|---|---|---|---|---|
| *RCS* of PM–FMS and MFP (%) | *NPC* RTL | *NPC* PM–FMS | *NPC* MFP | *RCS* of PM–FMS and MFP (%) | *NPC* RTL | *NPC* PM–FMS | *NPC* MFP |
| 20 | $856 \pm 58$ | $877 \pm 85$ | $803 \pm 84$ | 20 | $1008 \pm 209$ | $1672 \pm 284$ | $1496 \pm 281$ |
| 50 | $852 \pm 68$ | $749 \pm 71$ | $696 \pm 70$ | 50 | $1002 \pm 176$ | $1462 \pm 123$ | $1462 \pm 121$ |
| 80 | $846 \pm 84$ | $616 \pm 114$ | $573 \pm 70$ | 80 | $1013 \pm 197$ | $1281 \pm 170$ | $1281 \pm 169$ |

Table 1. Scenario B: Estimates of *NPC*s of RTL, PM–FMS and MFP for different values of *RCS* and *CV* (kEURO).

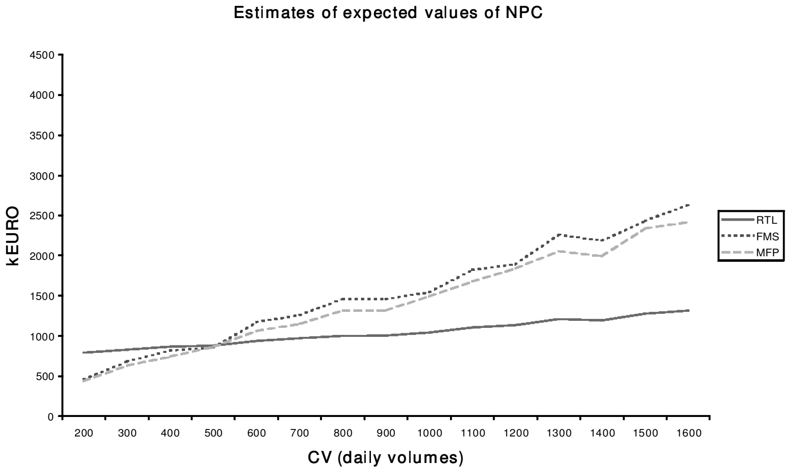


Figure 3. Scenario B: average values of *NPC*s of RTL, MFP and PM–FMS as a function of *CV*.

demand values of the products in the last years have been collected. On average, peak on the market demand is $\sim$ 600 parts per day in the maturity period; products are at different stages of their life cycle. Because risk is not considered, we assume that *CV* values are equal to the collected peaks on the market demands of the real case. We also assume that quantities purchased by the market correspond to the real demand of the real case.

RTL systems are normally dedicated to only one product; therefore a set of eight different RTLs (with a total of 116 stations) is dimensioned to produce all the part types of the mix with their *CV*. It is assumed that a single RTL is acquired when the market requires the related product. A PM–FMS and the proposed system architecture MFP have been configured to produce the part mix for the planned time horizon. MFP and PM–FMS investment is differentiated in the time because of their high flexibility of expansion (Koren *et al.* 1999). In this scenario *RCS* of flexible systems is equal to 0% because we assume that the part mix represents all the products manufactured in the shop floor.

*NPC*s of the different system architectures are calculated using the historical values of the market demand for the given production mix (investment and operating cost are reported in table 2). It results that flexible systems perform better than rigid systems for the given mix of parts.

Machine investment cost of RTL is the highest because of the resource duplication due to the rigidity of RTL stations; on the other hand, flexible systems are expanded simply by adding new machines. Investment on material handling system is high in MFP because of the large number of part carriers needed to face high flow of parts circulating in the system (the original cause is the reduced machine envelope that leads to only one part mounted on a fixture). Tool handling system investment in MFP is high due to the high cost of the tool carrier, even if the total number of copies of tools is reduced. In addition, labour cost in the new architecture is low due to the automation of the part loading. Because the speed of MC spindle is very high, operating tool cost in PM–FMS and MFP increases a lot proportionally to tool wear. As for modification cost, RTL machines have to be adapted to the

| | RTL | PM–FMS | MFP |
|---|---|---|---|
| Machine | 4218 | 4156 | 3325 |
| Material handling system | 603 | 761 | 1026 |
| Tool handling system | 201 | 284 | 232 |
| Supervisor | 0 | 83 | 83 |
| Total investment cost (kECU) | 5022 | 5284 | 4666 |
| Labour | 706 | 792 | 416 |
| Tool wear | 1889 | 2626 | 2626 |
| Maintenance | 314 | 633 | 633 |
| Power | 116 | 696 | 696 |
| Modification | 675 | Negligible | Negligible |
| Total operating cost | 3700 | 4747 | 4371 |
| Net present cost | 4413 | 3940 | 2065 |

Table 2. Scenario C: investment and operating cost of RTL, PM–FMS and MFP (kEURO referred to the initial time).

modified part features while systems with flexible machines, e.g. PM–FMS and MFP, need only an easy change of the part program and therefore costs are negligible in comparison with RTL.

### 3.5. *Scenario D: mix of products, uncertainty in market demand*

This scenario is similar to the previous one. The difference is that uncertainty of market demand is now considered. In this case the firm knows the product and the length of its life cycle but it does not know the volumes that the market will require in the future. However, some information is available because contract negotiation forces the firm to dimension the system on the basis of the *CV*s of products. In this case *CV* is, on average, equal to the peak value collected from the real demand divided by 0.53 (this value has been estimated from the real case); note that in scenario C the peak value of the demand corresponds to *CV*. As a consequence, systems dimensioned in scenario D have a total capacity greater than or equal to that of scenario C.

It is assumed that every 6 months the firm decides if the system should be expanded or not. In taking the capacity expansion decision the firm can use the new information available; e.g. if at time *t* the firm knows from its customers that a product can never reach its original *CV*, the firm can use this new piece of information. Indeed the exceeding system capacity can be allocated to the other products of the analysed mix in the following time periods. Table 3 shows the values of the *NPC* for a case in which *RCS* of flexible systems is equal to 0%.

The scenarios show the behaviour of *NPC*s of different production systems. It results that flexible systems are more productive than rigid systems for a set of parts. In particular it seems that the new architecture MFP is the most profitable in the cases analysed in the paper. Note that although the case considered is a fairly representative one, one should not conclude, without further empirical comparisons,

| *NPC* RTL | *NPC* PM–FMS | *NPC* MFP |
|---|---|---|
| 6077 | 4194 | 3708 |

Table 3. Scenario D: *NPC* of RTL, PM–FMS and MFP (kEURO).

that the MFP system is superior in general. Our results nevertheless support the claim that MFP can certainly be an interesting alternative in medium–high volume production environments.

## 4. Conclusion

This paper has described a new system architecture that addresses requirements of firms operating in the field of components for the automotive industry. An investment analysis demonstrates that the new system architecture can be more profitable in comparison with RTL and PM–FMS for a representative case of data and confirms the new market trends toward customized flexible systems for the production of parts in medium volumes. The analysis takes into account the effect of production mix and uncertainty of market demand on the performance of rigid and flexible production systems. Future work will be devoted to the extension of the comparison among different system architectures by considering other sources of randomness, e.g. the introduction of new products, or the variable length of the life cycle of products, or the reliability of machines. It would also be interesting to design a 'performance map' which depicts the areas in which a given system architecture performs better.

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