Focused Flexibility in Production Systems

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Abstract Manufacturing flexibility is seen as the main mechanism for surviving in the present market environment. Companies acquire systems with a high degree of flexibility to cope with frequent production volume changes and evolutions of the technological requirements of products. However, literature and industrial experience show that flexibility is not always a well-defined concept. Therefore it is really complex to understand and use flexibility during system design process. Indeed, the development of structured approaches to support the system design by considering basic flexibility forms is still an open issue. This work presents an Ontology on Flexibility aiming at providing a standard method to analyze flexibility. Firstly, it contributes in systemizing the large number of existing flexibility definitions and classifications. Secondly, it can be used to analyze real systems and to better understand their characteristics in terms of flexibility. Finally this ontology represents a key point of a general approach to design production system with the right level of flexibility.

Keywords: Focused Flexibility Manufacturing Systems (FFMSs), Manufacturing system design, Ontology on Flexibility

3.1 The Importance of Manufacturing Flexibility in Uncertain Production Contexts

Companies producing mechanical components to be assembled into final products produced in high volumes, in order to remain competitive, must deal with critical factors such as: tight tolerances on the parts, short lead times, frequent market changes and pressure on costs (Matta *et al.* 2000; Tolio 2008). Obtaining optimality in each of these areas can be difficult and companies often define production objectives as trade-offs among these critical factors (Chryssolouris 1996).

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The flexibility degree of a manufacturing system represents a critical issue within the system design phase. On the one hand, it is considered a fundamental requirement for firms competing in a reactive or a proactive way. On the other hand, flexibility is not always a desirable characteristic of a system. This point needs to be clarified since in many cases flexibility can jeopardize the profitability of the firm. It is rather frequent to find in the literature descriptions of industrial situations where flexible manufacturing systems have unsatisfactory performance (Koren *et al.* 1999; Landers 2000), cases where the available flexibility remains unused (Sethi and Sethi 1990; Matta *et al.* 2000), or cases where the management perceives flexibility more as an undesirable complication than a potential advantage for the firm (Stecke 1985).

From the scientific perspective, focusing the flexibility of a production system on the specific needs represents a particularly challenging problem. In fact, the customization of system flexibility provides economical advantages in terms of system investment costs, but, on the other hand, tuning the flexibility on the production problem reduces some of the safety margins, which allows decoupling the phases of manufacturing system design (Tolio and Valente 2008). One of the key issues is that focused flexibility asks for a very careful risk appraisal. To reach this goal all activities ranging from the detailed definition of the manufacturing strategy to the configuration and reconfiguration of production systems must be redesigned and strictly integrated, thus highlighting the need of combining and harmonizing different types of knowledge which are all essential to obtain a competitive solution.

3.1.1 Focused Flexibility Manufacturing Systems - FFMSs

The simultaneous need of flexibility and productivity is not well addressed by available production systems, which tend to propose pre-selected types of flexibility to introduce in the system. Traditionally, rigid transfer lines (RTL) have been adopted for the production of small families of part types (one or few part types) to be produced in high volumes (Koren *et al.* 1998). Since in RTLs scalability is low, RTLs are usually designed according to the maximum market demand that the firm forecasts to satisfy in the future (volume flexibility); as a consequence, in many situations RTLs do not operate at their full capacity since their designed volume flexibility is frequently oversized. On the other hand, flexible manufacturing systems (FMSs) and parallel machine-FMSs (PM-FMSs) have been adopted for the production of large mixes of parts to be produced in small quantities (Grieco *et al.* 2002; Hutchinson and Pflughoeft 1994). FMSs are conceived to react to most of the possible product changes. The investment to acquire a FMS is very high and it considerably affects the cost to produce a part. Indeed their flexibility is frequently too large and expensive. This is extremely evident for instance in the case producers of components for the automotive industry (Sethi and Sethi

1990) where even if the types of products are rather stable still fully flexible FMSs are frequently adopted.

Therefore, in many situations, there is a need to address the trade-off between productivity and flexibility by means of manufacturing systems having the minimum level of flexibility required by the production problem on hand (Tolio and Valente 2007). This new class of production systems can be named Focused Flexibility Manufacturing Systems (FFMSs) (Tolio and Valente 2006).

The flexibility degree in FFMSs is related to the required ability to cope with volume, mix and technological changes, and it must take into account both present and future changes. The required level of system flexibility impacts on the architecture of the system and the explicit design of flexibility often leads to hybrid systems (Matta *et al.* 2001), i.e. automated integrated systems in which parts can be processed by both general purpose and dedicated machines. This is a key issue of FFMSs and results from the matching of two different features that characterize respectively FMSs and Dedicated Manufacturing Systems (DMSs) (Tolio 2008). Another way FFMSs reach their goal is by combining in the same system old and new machines. In other words, in FFMSs the customization of the flexibility for a certain production problem explicitly addresses the trade-off between flexibility and productivity and tries to maximize system profitability.

As it can be noticed, FFMSs differ from Reconfigurable Manufacturing Systems (RMSs) (Koren *et al.* 1999; Ling *et al.* 1999; Landers 2000) in the timing of flexibility acquisition and in the explicit analysis of the cost of flexibility. Indeed the key idea of RMSs is to provide in each moment the production system exactly with the capabilities required by the production problem on hand and to modify the system if the needs change with time. Frequently, the reconfigurability option needs to be considered at system level since in many cases available hardware and software devices are not mature enough to support reconfigurability at machine level (Wiendhal *et al.* 2007). The FFMSs consider reconfigurability and flexibility as two options and mix them on the basis of their costs. For instance, it could be cheaper to acquire more flexibility than the amount strictly required by the present production in order to avoid possible future system reconfigurations and ramp-ups. Another example to pursue the extra-flexibility option, involving lower economical investments, is to design the system introducing, among the others, old machines that have been totally depreciated but are still very flexible. In this case, FFMSs have some extra-flexibility designed to cope with future production changes, i.e. a degree of flexibility tuned both on present and future part families. The strategic decision of designing the reconfigurability option or the extra-flexibility option depends on the result of costs analysis (Tolio *et al.* 2007; Tolio 2008).

Although the concept of FFMS would fit particularly well in the current production context, frequently the tradition and know-how of both machine tool builders and production system users play a crucial role in hindering the exploitation of this idea. In fact even if firms often agree with the focused flexibility vision nevertheless the lack of a clear definition of the flexibility design problem prevents the exploitation of this approach. In order to overcome this limitation new frameworks for defining the manufacturing system flexibility have to be developed together with methodologies and tools to design the degree of flexibility on the basis of the specific production problem.

3.2 Literature Review

Flexibility is the ability to change or react with little penalty in time, effort, cost or performance (Upton 1994) in order to cope with a set of production requirements (De Toni and Tonchia 1998). On the one hand internal requirements strictly related to production call for *internal flexibility*; on the other hand, when flexibility represents a competitive advantage for the company in relation to external turbulence, *external flexibility* is required.

A dominant feature of the literature, and an important step in providing a better understanding, is the use of taxonomies of flexibility, which classify different types of manufacturing flexibility. These categories are useful since they provide general types that can be used to distinguish one form of flexibility from another, as stated by Upton (1994). In order to characterize each important type of flexibility, Upton suggests that, if flexibility is an issue, questions regarding which changes and how often they happen should be asked. These drivers force the manufacturers to evaluate their ability to change their manufacturing systems and the penalty to face the change. This is a complex task in dynamic manufacturing contexts (Beach *et al.* 2000), as for instance the automotive, semiconductor, electronics and high tech markets, because products are affected by frequent changes in volume and technology.

The key issue highlighted in the literature is the multidimensional nature of flexibility. Many efforts, over time, have been dedicated to the development of taxonomies in which all the possible forms of flexibility are classified and characterized. Sethi and Sethi (1990) gave order to the exiting literature by proposing a classification where 11 different dimensions of flexibility are identified. Later on, Gerwin (1993) reduced to 9 forms of flexibility the framework provided by Sethi and Sethi (1990). Gupta and Somers (1996) developed an instrument to measure manufacturing flexibility and they also analyzed the relation among business strategy, manufacturing flexibility and performance: moreover, they carried out an empirical study to validate the dimensions of flexibility defined by Sethi and Sethi (1990). De Toni and Tonchia (1998) definitely contributed to the activity of conceptual systemization of the earlier works on flexibility. Their work proposes a classification framework consisting of six main aspects of manufacturing flexibility, such as the definition of flexibility, factors which determine the need for flexibility and classification (dimensions) of flexibility (hierarchical, by phases, temporal, by object of variation, or based on a mixture of the previous dimensions).

This framework has been used to classify more than twenty years of research contributions on the topic.

A further contribution is proposed by Zhang *et al.* (2003) where manufacturing flexibility and its sub-dimensions are described as integral components of value chain flexibility. ElMaraghy (2005) links the concept of manufacturing system lifecycle to manufacturing systems flexibility and reconfigurability; this paper presents the most recent views of a panel of experts from Academia and Industry on the comparisons between flexible and reconfigurable manufacturing.

Although much effort has been devoted in the literature to the analysis of flexibility, as a solution to cope with uncertainty in the market and to support the manufacturing strategy, the link between the need for flexibility and the design of manufacturing systems is still very weak (Tolio and Valente 2006). In this area, examples are provided of the relation between the level of flexibility embedded into the system and corresponding system performance (Koren *et al.* 1999; Landers 2000) as well as critical analyses of production systems characterized by extra-flexibility (Sethi and Sethi 1990; Matta *et al.* 2000). However, methodologies to design systems with predefined levels of flexibility are still almost missing.

3.3 Proposal of an Ontology on Flexibility

In the previous sections, the importance of designing manufacturing systems endowed with the right degree of flexibility has been underlined. This task is complex because it requires addressing internal and external issues; in particular, product and processes are easily and frequently changed by market and manufacturing strategies, while production systems must cope with relevant inertia to changes. The goal of this work consists of providing a contribution to fill the modeling gap between a production problem and the manufacturing system best suited to face it. This gap, for instance, consists of a lack of proper knowledge concerning the logical framework required to deal with the problem, the type of information to be collected and the methodologies and tools to be applied to jointly consider information of different nature. Considering the state of art for system design and system flexibility analysis, three main issues can be identified to reach the final goal:

1. Identification of Basic Flexibility Forms which can lead the solution of the System Design problem;
2. Integration of new concepts (e.g. Reconfigurability and Changeability) in the Flexibility theory;
3. Design of Production Systems characterized by the right degree of flexibility, translating Flexibility Forms into System Specifications.

In this section, the first two issues will be addressed, while the third one is dealt with in Section 3.5. Considerable effort has been devoted to the definition of different forms of flexibility to describe the characteristics of a manufacturing system (see Section 3.2). Some authors have pointed out that a given form of flexibility is the capability of reacting to a well-defined type of "stimulus", which can be experienced by the manufacturing system (Upton 1994; Correa and Slack 1996; De Toni and Tonchia 1998; Grubbstrom and Olhanger 1997). Other authors have shown that a given form of flexibility may support various proactive strategies of the firm (Gupta and Goyal 1989; Sethi and Sethi 1990; Hyun and Ahn 1992; Gerwin 1993; Gupta and Somers 1996). Since both the stimuli acting on the firm and the proactive strategies of the firm may differ, there is a need for various forms of flexibility. The result is that the number of types of flexibility proposed in the literature is growing and, even if some rationalization has taken place, still the number is very high. Also, different authors tend to assign to a given type of flexibility slightly different meaning given the different fields of application they take as reference. Moreover, there is ambiguity among flexibility forms and other concepts (e.g. Expansion Flexibility vs. Reconfigurability). This situation cannot be overcome since it depends on the fact that a given form of flexibility is actually an answer to a very specific problem. Since the number of problems is uncountable, the number of forms of flexibility, which may be devised, is also in principle uncountable.

In this chapter, an ontology is proposed where each form of flexibility is considered as a recipe to tackle a specific situation. According to the first issue (e.g. the identification of Basic Flexibility Forms which can lead the System Design problem), the key question is whether there are some basic *dimensions* of flexibility from which all the various *forms* of flexibility may be obtained by means of a specific combination tuned for specific problems. *Dimensions* are general theoretical concepts and should not find a direct implementation. Instead, dimensions are embedded in the various *forms* of flexibility, which can be found in specific applications. For this reason, *dimensions* should not be measured but should be treated as logical categories.

In this view, to solve specific problems there is the need of system specific *forms* of flexibility, which may be implemented and measured but in turn they incorporate a combination of the basic *dimensions* of flexibility.

If such a set of *dimensions* can be defined, one desirable property is that each *dimension* in the set should be orthogonal to the other *dimensions* in the sense that the *dimensions* in the set are independent and that one *dimension* cannot be obtained as a combination of the other ones. Another desirable property is completeness, i.e. each *form* of flexibility should be derived as a specific combination of the given *dimensions*. A set of flexibility *dimensions* is proposed, as reported in Table 3.1, to answer to these requirements.

Table 3.1 Basic Flexibility Dimensions.

Basic Flexibility Dimension	Definition
Capacity	The system can execute the same operations at a different scale
Functionality	The system can execute different operations (different features, different level of precision, etc.)
Process	The system can obtain the same result in different ways
Production Planning	The system can change the order of execution or the resource assignment to obtain the same result

The proposed set is orthogonal, indeed it is impossible to obtain one dimension as a combination of the others A good combination of these *dimensions* makes the *form* of flexibility a valuable answer to the specific problems a company may encounter.

Each *dimension* needs to be further specified by attributes, as proposed by Upton (1994): attributes can be used for each of the four *dimensions*. Table 3.2 provides the *attribute* definitions. The goal here is not to derive a metrics to measure the *dimensions*; the idea is that the concepts contained in the *dimensions* cannot be completely defined if the described attributes are not introduced. Therefore, attributes are treated here at a conceptual level.

Table 3.2 Flexibility Attributes.

Attribute	Definition
Range	Range expresses the extension of the differences among the various ways of behaving of the system under a given dimension. Range increases with the diversity of the set of options or alternatives, which may be accomplished. For example in the Functionality dimensions it represents how diverse is the set of different operations, which can be executed by the system.
Resolution	Resolution expresses how close are the alternatives within the range of a given dimension. Resolution increases with the number of viable alternatives if they are uniformly distributed within the range. For example in the Functionality dimensions it expresses how small is the distance between similar but different operations, which can be done by the system.
Mobility	Mobility within the range. Mobility expresses the ease with which it is possible to modify the behavior under a given dimension. In fact, in order to start operating at a different point on a given dimension of change, there will be some transition penalty. Low values of transition penalties imply mobility. For instance in the Functionality dimension it may represent how easily it is possible to move from doing one operation to performing another one.
Uniformity	Uniformity within the range. Uniformity expresses how the performance of the system varies while moving within the range. If the performance is similar then the uniformity is high. For example in the Functionality dimension it may represent the difference in capability or costs while executing different operations.

To completely define the various forms of flexibility another concept must be introduced. A given flexibility *form* specified by its *dimension* and *attributes* may be present in a given system. However, another system may exist where the considered *form* is not present but it can be acquired so that, after this acquisition, the two systems have similar capabilities. This second situation differs from the first one in the fact that the system is one step behind because to obtain the same capability some actions must be taken. However, the fact that these actions can be taken means that the system has some pre-disposition, which makes it different from a system, which cannot be modified. This pre-disposition is normally called in the literature "Reconfigurability". The fact that a system is one step behind under a given *form* suggests the concept of a ladder with different *levels*. At the top level of the ladder the given *dimension* considered is fully operational. At the lower levels of the ladder more steps must be taken in order to reach the top level. The *levels* of the ladder are defined in Table 3.3.

Table 3.3 Basic Flexibility Levels.

Basic Flexibility Level	Definition
Level 1 (Flexibility)	The system has the ability
Level 2 (Reconfigurability)	The system can acquire the ability already having the enablers
Level 3 (Changeability)	The system can acquire the enablers

Through the definition of Basic Flexibility *Levels*, the proposed ontology allows to unify the concepts of Flexibility, Reconfigurability and Changeability, coping with the second issue previously identified ('Integration of new concepts in the Flexibility theory'). All these concepts deal with modifications in Production Systems and the difference among them consists of the timing, cost and number of steps necessary to implement a modification.

A basic flexibility *form* is the combination of a specific *dimension* (specified by its attributes) and of a specific *level* of the ladder. Therefore various basic *forms* of flexibility can be derived. By combining basic *forms* of flexibility, compound *forms* of flexibility can be obtained. A graphical representation of the proposed ontology through an UML Class Diagram is reported in Figure 3.1.

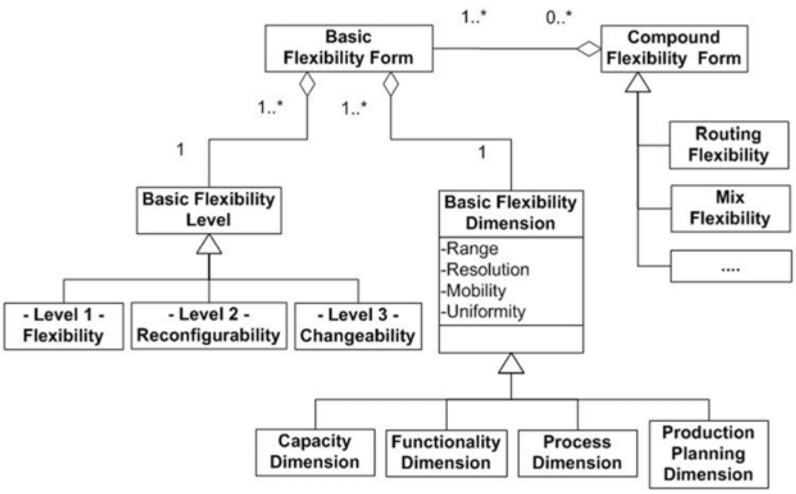


Fig. 3.1 Structure of the Ontology on Flexibility.

To test the viability of the proposed framework two analyses are carried out and presented. Firstly, the possibility to map all the *forms* of flexibility described in the existing literature through the four basic *dimensions* is investigated. Secondly, the attention is focused on the *forms* of flexibility applied in the industrial production context. Herein, some industrial cases are analyzed using the framework to understand how the basic *dimensions* of flexibility are combined.

The flexibility *forms* defined in the literature have been mapped according to the basic *dimensions* of flexibility defined above. Globally, 109 *forms* (both basic *forms* and compound *forms*) of flexibility have been mapped by Tolio *et al.* (2008). Three examples of flexibility *form* analysis are reported in Table 3.4. The flexibility *forms* have been mapped defining which *Basic Flexibility Dimensions* are involved and at which *Basic Flexibility Levels*. For instance, Volume Flexibility as reported by Sethi and Sethi (1990) corresponds to Capacity Flexibility at Level 1.

Table 3.4 Extract of the *flexibility forms* found in the literature mapped according to the proposed ontology

Compound Flexibility Form	Paper	Capacity Flexibility	Functionality Flexibility	Process Flexibility	Production Planning Flexibility
Expansion	(Sethi and Sethi 1990)	Level 2, Level 3	Level 2, Level 3	-	-
Expansion	(Parker and Wirth 1999)	Level 2, Level 3	-	-	-
Volume	(Sethi and Sethi 1990)	Level 1	-	-	-

3.4 Analysis of Real Systems

The proposed Ontology on Flexibility has been validated by analyzing some real production systems. The goal was to verify whether the requirements of flexibility addressed by these systems could be described using the proposed flexibility *dimensions* and *levels*; moreover, the cases have been studied paying attention to the topic of Focused Flexibility, finding out how different manufacturing system solutions cope with the need of flexibility. The following case studies have been considered:

1. Lajous Industries SA
2. Riello Sistemi S.p.A.

These industrial cases have been selected since they exemplify the need of rationalizing system flexibility. Starting from the description of the production context in which firms operate as well as the related designed production system, the current system solution will be evaluated using the provided ontology on flexibility.

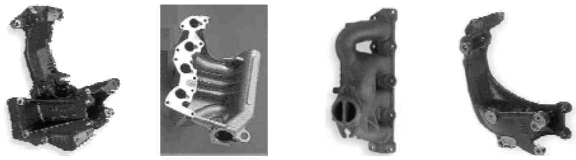
3.4.1 Lajous Industries SA case study

Lajous Industries SA, which belongs to the industrial group Peugeot-Japy, is the French leader in the market of production of metal components for automotive industry. The components produced by Lajous can be divided into the following categories:

- Engine related components (e.g. manifolds, engine supports and accessories, pump bodies, fly wheels, oil cups, *etc.*);
- Chassis/suspensions/brakes (e.g. brake drums, pivot supports, *etc.*);
- Transmission components (e.g. synchronisation rings, differential boxes, *etc.*);

Many important firms in the automotive sector are customers of Lajous, as for instance Audi, Pegeout-Citroen, Ford France SA, Magneti Minarelli, New Holland and Renault. Lajous pays a strong attention to the problem of total quality and important efforts are directed towards the introduction of Lean Production and Total Production Maintenance concepts.

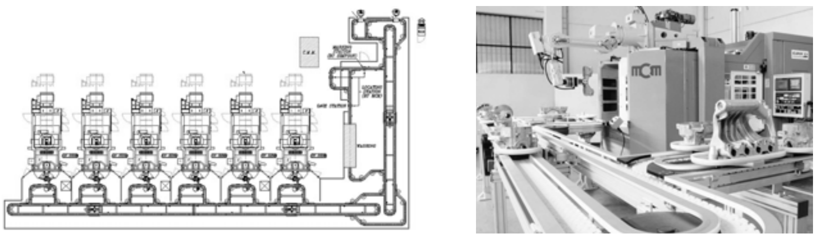
The plant of Lajous at Compiegne (France) was studied within the Mod-Flex-Prod European project (EU Project BE96-3883); the plant consisted of approximately 600 machine tools. A part of the global production problem was characterized by a family of metal components, which can be clustered in few families of product types described by technological and volume evolutions. In particular, in the portion of the system studied, at a first stage the firm had to produce a family of three products: codes A, B, C (Figure 3.2). The firm forecasted that a new product type, code D, could be produced at a later time. In this case, technological and mix changes would characterize the part family evolution.



a b c d

Fig. 3.2 a. Code A, an engine support; b. Code B, an alloy manifold; c. Code C, a cast-iron manifold; d. Code D, an engine support.

Therefore, Lajous decided to install a new type of FMS (Figure 3.3.a) proposed by MCM S.p.A. to address the production problem characterized by frequent technological and volume changes of products.



a b

Fig. 3.3 a. Lajous production system layout; b. Clamping robot & conveyor belt by MCM S.p.A.

In the system, parts flow on a conveyor belt and are loaded by a clamping robot on the fixtures, which equip the various machining centers (Figure 3.3.b). This solution allows a significant reduction in the number of pallets and fixtures in the system and eliminates manual load and unload of the parts on/from the fixtures. Therefore, the implemented system can work during unmanned shifts, and the production is not limited by the number of fixtures available in the system as it happens in traditional FMSs. This solution, however, does not allow a frequent change of product mix because fixtures cannot be loaded/unloaded automatically on/from the machines.

Therefore, the rationale adopted by the firm consisted of purchasing a high level of system flexibility in order to face changes in product demands and in product versions coming from different customers. At the same time an effort was made to focus the flexibility taking into account that at a given time the number of products of the mix is rather small while production volumes are high. The production system is composed by identical machining centers; therefore, Functionality flexibility at Level 1 is guaranteed because general purpose machining centers allow executing a wide range of operations with a good capability and require very short setup times.

Considering the size and the weight of the fixtures the manual change of fixtures is a rather complex and time consuming operation lasting more than one shift. Therefore the functionality mobility of the system is not extremely high which is coherent with the production problem where the mix is stable in the short time. The savings in terms of pallets and fixtures result in a reduction of system flexibility, which has been focused on the specific production problem on hand.

The conveyor belt allows moving the parts between any couple of stations, therefore, the Functionality flexibility of the transport system is guaranteed at Level 1. Also, the availability of a conveyor belt to connect the various machines allows to easily add/remove machines form the system since it is rather easy to modify the layout of the transport system. Therefore, the Capacity dimension is addressed at Level 2, which again is coherent with a situation where volume changes can be foreseen in advance and may be rather significant.

Both the characteristics of the machines and of the conveyor belt give the system also Production Planning flexibility at Level 1. However, the fact that fixtures are stable on the machines limits the way parts can be assigned to machines. The analysis of the manufacturing system according to the ontology on flexibility (see Section 3.3) is reported in Table 3.5, where the basic flexibility *dimensions* embedded into the Lajous manufacturing system are represented.

Table 3.5 Lajous case flexibility analysis.

Capacity Flexibility	Functionality Flexibility	Process Flexibility	Production Planning Flexibility
Level 2	Level 1	-	Level 1

3.4.2 Riello Sistemi case study

Gruppo Riello Sistemi S.p.A. is a machine tool manufacturer whose plants are distributed in Europe, North America and China. The set of products designed and manufactured by Riello Sistemi consists of production lines, in particular rotary table transfer machines (TTRs), flexible transfer machines (VFX) and machining centers (MC). Riello Sistemi proposes highly customized solutions, which always present a mix of standardized and specialized components. Therefore, each line solution can be considered as unique. In this environment, the phase of design of the product-line plays a key role. Some examples of transfer lines produced by Riello Sistemi are reported in Figure 3.4. Typical features of transfer lines are:

- Presence of up to 14 stations, with up to 3 main spindles in each station;
- Many tools contemporary working (up to 36 if single tools are used or even more with multi-spindle unit);

- Every spindle has usually 1 or 2 controlled axes, but may have up to 4;
- The line is dedicated to a single component or to a family of similar components and often it integrates special devices;
- Very high production rate over investment costs ratio;
- Low space occupation in the workshop.

Fig. 3.4 Examples of transfer machines produced by Riello Sistemi.

Given the high turbulence of the market in which its customers operate (automotive, aeronautics, electronic devices sectors), Riello Sistemi S.p.A. decided in the last decade to endow its production line with a certain degree of flexibility, starting from its conception and design. The idea was to change the characteristics of transfer lines, which were generally rigid solutions for high production volume, in order to include the possibility of modifying the line structure when some changes in the market happen. In particular, common customer requirements are easy and quick machine set-up and machine adaptation to geometrical shape modification of the parts to be machined.

In order to achieve this goal, a set of technical solutions has been introduced, involving both the software and the hardware of the machine. Regarding the software, the adoption of flexible control, through the use of programmable CNC controls, allows to rapidly change sequences and priorities. Regarding the hardware, devices (e.g. linear or angular slides manually operated), which can modify the access direction of working spindles, have been introduced together with technical solutions to allow the implementation of additional rotary axes when needed. Some of the modular components enabling the transfer line reconfiguration are reported in Figure 3.5.

a b c

Fig. 3.5 a. Cross slide; b. Rotary table; c. Unit head.

To show the importance of the design phase while proposing a customized reconfigurable transfer line solution, a real transfer reconfiguration case is reported.

In this case, the customer needed special equipment to produce three product types named part A, B and C. While the customer assumed that part A would remain constant in the future, both in terms of technological features and in terms of volumes (1000000 parts/year), products B and C were supposed to change after 18 months, in terms of technological features, while remaining constant in terms of volumes (500000 parts/year for B and C). All the products were steering gear holders and the modification of products B and C into D and E consisted of the elimination of the part named "top hat" and the reorientation of some features. The sketches of product B and C and the modification of the codes into product D and E are reported in Figure 3.6.

Fig. 3.6 Modification of product B and C into products D and E expected after 18 months.

The knowledge about the new product variants expected after 18 months allowed the system designer to propose a reconfigurable solution enabling the system modification with low cost. Two transfer lines were designed, one dedicated to product A, which was stable over the system life cycle, and one dedicated to products B and C, which were expected to evolve. Each transfer line consisted of two machines in parallel, in order to guarantee the satisfaction of the throughput constraint. Indeed, in this type of systems, raw parts enter the system at the first station and must visit all the stations in the line before exiting as a finished product.

After the analysis of the impact of product modifications on the manufacturing process, the technical solutions, which allow modifying the structure of the line to tackle the process modifications were analyzed. In particular, the possibility of changing the loading slide and the clamping fixtures were introduced together with the possibility of modifying the position of some working units using hydraulic slides. Finally, the possibility of changing multi-spindle heads was included.

The second line of the manufacturing system designed by Riello for product B and C has been endowed with the ability of doing different products, thus working different product features, with the same set of resources; therefore, the case study is characterized by Functionality flexibility at Level 1 since the second line can process both product B and C requiring short setup times.

The system has been designed to be easily reconfigured thanks to a set of technical solutions, which allow rapidly changing its configuration, without high costs and time. This means that the proposed case study is an example of Functionality flexibility at Level 2 as well.

Regarding the other basic dimensions, few information are available to evaluate if Capacity flexibility has been designed; despite the production volumes of the different codes seem to remain unchanged over time it is reasonable that the customer asked to design a system with some overcapacity (Capacity flexibility at Level 1). Finally, both Process and Production Planning flexibility can be hardly considered while dealing with transfer lines. In fact, since the flow of parts is rigid it is a challenge to modify the production sequence or to provide alternative processes to realize the same product. The analysis of Riello system solution is summarized in Table 3.6.

While in Section 3.4.1 it was shown how it is possible to reduce the investment of flexibility in a FMS, in this section it has been shown how a rigid transfer line can be endowed with a certain level of flexibility to cope with production changes. Therefore, also in this case it is possible to say that the proposed solution is an example of Focused Flexibility. The level of focalization is very high because the system and its possible reconfigurations have been tailored to a defined set of parts.

Table 3.6 Riello case flexibility analysis.

Capacity Flexibility	Functionality Flexibility	Process Flexibility	Production Planning Flexibility
Level 1	Level 1, Level 2	-	-

3.5 Using the Ontology on Flexibility to support System Design

Traditionally, models to support the design of production system embedding flexibility are based on the definition and implementation of flexibility forms, as is represented in Figure 3.7 (Sethi and Sethi 1990; Gerwin 1993; Upton 1994; Chryssolouris 2006). It can be difficult to adopt this kind of approach because it requires the definition, measurement and implementation of abstract concepts such as flexibility forms. Section 3.3 and other works (e.g. Tolio *et al.* 2008) have shown that many definitions of flexibility forms are available and all of them can be the right ones if applied to a particular context; therefore, how should the flexibility forms be chosen?

The measurement of flexibility forms is critical as well, because there is no standardized measurement unit and the measure itself tends to be subjective. Finally, even if precise measures of the required flexibility were obtained, it would be necessary to translate these abstract values into a real production system. But how to carry out this task is not clear.

Fig. 3.7 Design of Flexibility.

Indeed, in practice, it is very difficult to use synthetic flexibility values to design complex systems because, due to the interaction among system components, there is no simple mapping between the required flexibility and the physical components that are able to provide it. Therefore, in this section a different approach for system design is presented (Figure 3.8). This general approach does not try to design a system with a predefined level of flexibility, but it aims at designing production systems, which are able to face the production problem on hand with the minimum economical effort over the system lifecycle.

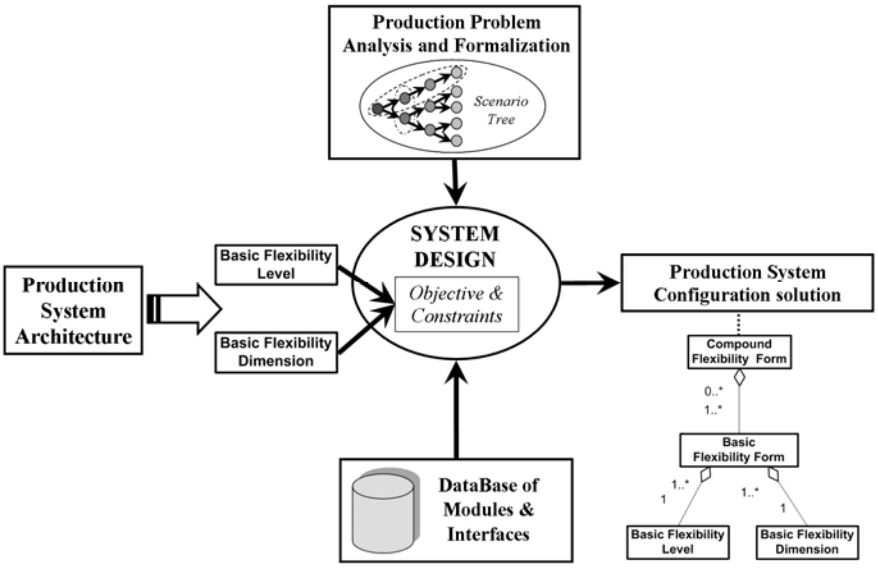


Fig. 3.8 Design of Production System with Focused Flexibility.

The proposed approach is based on a careful analysis of the manufacturing environment. In fact, a Production Problem Analysis and Formalization activity (upper box in Figure 3.8) is necessary to gather data about products and processes (for instance production volumes and product technological requirements), which define the present and future production problems to be addressed (Tolio and Valente 2007; Cantamessa *et al.* 2007). The different nature of the information to be handled during the production problem analysis highlights the need to support this activity by a proper formalism; the book by Bernard and Tichkiewitch (2008) presents some contributions about this topic. It must be noted that if no future information is available then the whole System Design approach collapses and the task of designing the right degree of flexibility becomes meaningless. Probably in this case the tendency would be to buy a system incorporating the maximum amount of flexibility as an answer to complete uncertainty about the future.

Therefore, the formalization of production problems should take into account also dynamic aspects. In fact, production problems are not static and can evolve during time (SPECIES 2008); system flexibility can be seen as a means to answer to this variability. A possible way to formalize the evolution of the production problem characteristics consists in dividing the planning horizon into periods and adopting a scenario tree approach (Ahmed 2003; Tolio and Valente 2008).

Once the production problem has been formalized, the structured information is used by a solution engine, here named *System Design* (central circle in Figure 3.8). Together with formalized information, the engine also receives as input the Database of Modules and Interfaces (lower box in Figure 3.8). This database contains information about devices that can be used inside a system (e.g. machining centers, transporters, pallets, buffers, etc.); moreover, since these modules must be integrated within a system, the database includes the interfaces among these devices. The *System Design* works finding a solution by matching system characteristic with the production problem at hand. This matching is achieved thanks to the objective and constraints, which are generated following the *Basic Flexibility Levels* and *Basic Flexibility Dimensions.* In fact, the main goal of the proposed Ontology on Flexibility (see Section 3.3) consists of supporting the system design phase. *Basic Flexibility Levels* and *Dimensions* lead the definition of the structural constraints while Production Problem Formalization and the Database of Modules and Interfaces provide the numerical data to be inserted in these constraints. Therefore, the ontology helps to match the system requirements, expressed by the Production Problem Formalization, with the available resource options, expressed by the Database of Modules and Interfaces. In this way, the flexibility degree required by the system is not explicitly dimensioned but it becomes an implicit output of the System Design phase.

Constraints can be divided into four groups according to the *Basic Flexibility Dimensions*. Acting on the constraints it is possible to implicitly define the Flexibility embedded in the System. For example:

- *Process Constraints* limit the choice of the process plan to adopt to process a type of product;
- *Functionality Constraints* deal with the assignment of operations to resource types;
- *Production Planning Constraints* deal with the assignment of operations to specific resources;
- *Capacity Constraints* limit the selection of the number of resources to be introduced in a system.

Beyond the Basic Flexibility Dimensions, a system design approach should consider also the *Basic Flexibility Levels*. This means that it is possible to cope with the evolution of the production problems by means of Flexibility, Reconfigurability or Changeability. Mathematical methods such as Stochastic Programming (Birge and Louveaux 1997) and Real Options Analysis (Copeland and Antikarov 2001) allow exploiting the concept of levels by clearly separating the configuration decisions which must be taken immediately from those which can be taken at a later time. In this way, constraints and decision variables incorporate the concept of Flexibility Levels.

The generation of objectives and constraints described so far is influenced by the decisions about the Production System Architecture. An architecture defines the general structure of a system and how the modules of the system can interact. Examples of production system architectures are Rigid Transfer Lines, Flexible Transfer Lines, Flexible Manufacturing Systems, Focused Flexibility Manufacturing Systems, Reconfigurable Manufacturing Systems, etc. Within the proposed *System Design* approach, architectural information (left box in Figure 3.8) is filtered by *Basic Flexibility Levels* and *Basic Flexibility Dimensions*; in this way, constraints are built following the structure imposed by the selected architecture.

The output of *System Design* is the Production System Configuration solution (right box in Figure 3.8). This solution can be analyzed according to the proposed ontology (see Section 3.4), which in this case can be seen as a classification and evaluation tool. In fact, each production system can be linked with a Compound Flexibility Form, which is the aggregation of different Basic Flexibility Forms. Indeed a designed system is a specific solution to a specific production problem.

3.6 Conclusions and Future Developments

The introduction of Focused flexibility may represent an important means to rationalize the way flexibility is embedded in manufacturing systems. Especially for mid- to high-volume production of well-identified families of products in continuous evolution focused flexibility may represent the missing species in manufacturing system evolution. However, in order to reap the benefits deriving from the acquisition of flexibility at the best time and in the right quantity many obstacles should be overcome. At first, a deeper understanding of the nature of flexibility asks for a clear definition of the dimensions of flexibility and for a formalization of the information required to describe future scenarios together with the risk connected with alternative choices. This could also simplify the system flexibility assessment, supporting the decision maker in evaluating the benefits coming from the use of such flexibility options, for instance by considering the make-to-stock option or capacity renting strategies. Secondly, a stronger ability to design the required flexibility should be developed. To this aim multistage decisions methodologies that explicitly take into account uncertain information about future scenarios are extremely valuable. Thirdly, the realization of new system architectures, new machines, devices and modules, new system supervisors are required in order to take advantage of the possibility of designing exactly the required flexibility and make focused flexibility a reality.

Some interesting solutions in this direction have been already provided by the most advanced companies. For instance, with more or less clear intents, machine tool builders are trying to create new system architectures which to some extent allow to focalize manufacturing flexibility. The aspects which in the long run can convince machine tool builders to provide innovative solutions to the customers depend on the profitability of FFMSs compared to traditional FMSs or to RMSs. Finally, another interesting aspect concerns the attention that both the system designer and user are showing concerning the analysis and formalization of present and future information. In fact, it often happens that the system user does not provide accurate forecasts to the system designer, jeopardizing the system design process. Therefore, on the one hand the support of a formalism allows the system user to collect and analyze data in a more structured way. On the other hand, the developed tool could guarantee that the system designer starts the system design process from the basis of a more comprehensive production problem description.

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