A Review on Manufacturing Flexibility

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Abstract The topic of Manufacturing Flexibility has been addressed by many scientific contributions in the past years, thus highlighting the relevance of the problem both at industrial and academic level. Internal and external issues need to be faced at the same time by designing a manufacturing system and its flexibility; in fact, products and processes are easily and frequently changed by market and manufacturing strategies, while production systems must cope with relevant inertia which slow down their changes. Therefore, a fundamental issue consists of filling the modeling gap between a production problem and the manufacturing system best suited to face it. Current literature provides a huge research on the analysis of flexibility, as a solution to cope with uncertainty in the market and to support the manufacturing strategy. However, the link between the need of flexibility and the design of manufacturing systems is still weak. This need includes a deeper understanding of the nature of flexibility and, in turn, a clear definition of the dimensions of flexibility. This chapter reviews the state of the art of the literature on manufacturing flexibility by following a conceptual framework to support flexibility formalizing process.

Keywords: Focused Flexibility Manufacturing Systems (FFMSs); Flexibility Review; Ontology on Flexibility

3.1 Current Literature on Manufacturing Flexibility Topic

Previous chapters of this book have highlighted the importance and the complexity of designing manufacturing system characterized by the right degree of flexibility. In particular, Chapter 2 has stressed the industrial interest in this innovative vision as well as the main design difficulties which arise when firms take first steps towards the focalization of flexibility.

The flexibility degree of a manufacturing system represents a critical issue within the system design phase. Even though it is often considered a fundamental requirement for competitive firms, it is not always a desirable characteristic of a system. Frequently the literature on flexibility provides industrial examples where flexible manufacturing systems have unsatisfactory performance (Koren et al. 1999; Landers 2000), cases where 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).

The analysis of the literature regarding the topic of manufacturing flexibility highlights the presence of four main categories of scientific works. In particular, within the first group many studies dealt with the analysis of the manufacturing flexibility meaning and its relationship with production problems. The second category includes works which tackled the classification of existing flexibility forms through taxonomies and conceptual frameworks. More recent papers focused on the development of approaches and models to support the system design while considering given system flexibility forms. These studies constitute the third category. However, despite those works provided important contributions on the manufacturing flexibility issue, the whole structure that supports the system design process starting from flexibility taxonomies is still weak. This aspect represents the core of the fourth literary group; in particular, concerning this last topic, an ontology on flexibility is briefly presented in order to contribute in systemizing the high number of definitions since they could be helpful within the system design phase.

Next sub-sections cover works and contributions to each one of the four literature categories.

3.1.1 Manufacturing Flexibility Analysis

The Analysis of Manufacturing Flexibility is faced by a large number of works. In this area a milestone work was presented by Upton (1994), who defined flexibility as the ability to change or react with low penalty in time, effort, cost or performance. Many authors considered manufacturing flexibility as the strategic answer to the current dynamic situation and the high degree of turbulence that affects the market (Chen and Tirupati 2002; Slack 1983; Gerwin 1987; Kumar 1987; Sethi and Sethi 1990). In many cases the analysis was supported by empirical studies as shown by Swamidass and Newell (1987). Other works studied how external changes are related to different forms of manufacturing flexibility and how they can be reduced. An example was provided by Gerwin (1993) as shown in Figure 3.1.

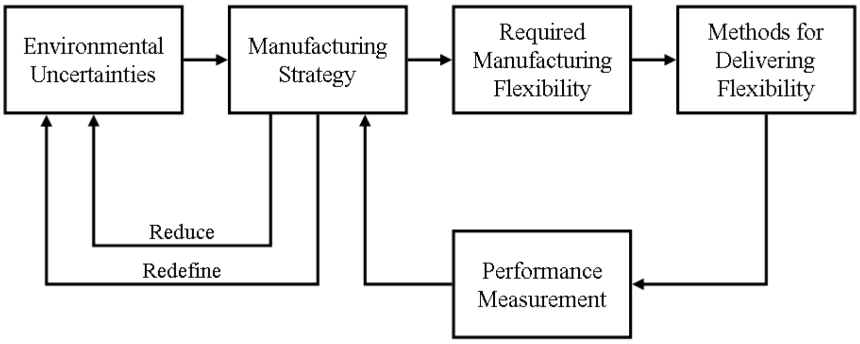

Fig. 3.1 Approach developed by Gerwin (1993)

These works highlighted the need for deeply investigating the relationship between the production requirements and manufacturing flexibility forms (Upton 1994; De Toni and Tonchia 1998). In particular, a key issue is to identify the flexibility forms which face internal requirements, called *internal flexibility*, and the flexibility forms that cope with external turbulence, called *external flexibility*. This vision was stressed by Correa and Slack (1996) that developed two main categories of requirements leading to the need of manufacturing flexibility: the environmental uncertainty and the variability of the output required by the system. These two phenomena are called *stimuli* and impact on the production system through planned and unplanned changes. Planned changes happen as a result of conscious managerial actions which aim at altering some aspects of the system or its relationships with the environment. Unplanned changes occur independently of the intentions of the company, but they call for a reaction. This type of changes will be called stimuli acting on the system.

Hyu and Ahn (1992) introduced the concept of proactive flexibility which takes into account possible future market changes. This allows firms to consider also strategies which are different from the simple reaction to market changes. In this sense, flexibility strongly impacts on the competitive levels of the firms. Gupta and Goyal (1989) proposed an approach to improve system flexibility in order to face short-term and long-term uncertainty. Goldhar and Jelinek (1983) identified in the flexibility concept the opportunity for companies to develop strategies mainly related to product variety while leaving markets characterized by scale economies. Grubbstrom and Olhanger (1997) analysis focused on the temporal factor: flexibility is related to the time necessary to respond to changing conditions and can be considered as the measure of the difference between two admissible states of the system.

3.1.2 *Taxonomies and Conceptual Frameworks*

The classification of existing flexibility forms through taxonomies and conceptual frameworks represents another topic which attracted many researchers. This body of literature addresses the importance of systemizing the knowledge concerning all the provided flexibility forms. Moreover, the multidimensional nature of flexibility justifies the efforts, over time, which have been dedicated to the development of taxonomies where all the possible forms of flexibility are classified and characterized.

Sethi and Sethi (1990) proposed a classification defining 11 different dimensions of flexibility. The provided framework consisted of three main groups: i) Component or Basic flexibilities that included Machine, Material-handling and Operation flexibilities; ii) System Flexibilities in which Process, Routing, Product, Volume, and Expansion flexibilities were considered; iii) Aggregate Flexibilities, e.g. Program, Product & Production, Market flexibilities. Moreover, the Organizational Structure as well as the Microprocessor Technology were transversally addressed by the authors. Gupta and Somers (1996) developed an instrument to measure manufacturing flexibility and carried out an empirical study to validate the dimensions of flexibility identified by Sethi and Sethi (1990). Gupta and Somers (1996) also examined the relationship among business strategy, manufacturing flexibility and performance. An empirical research over 269 companies showed that business strategy impacts on manufacturing flexibility that in turn impacts on organizational performance. Flexibility can be used as an adaptive response to both environmental uncertainty and proactively create market uncertainties for competition (Gupta and Goyal 1989; Gerwin 1993). The study of Gupta and Somers revealed that the 11 forms of flexibility proposed by Sethi and Sethi can be reduced to 9 forms of flexibility: Machine, Material-handling, Process, Routing, Volume, Program, Product & Production, Market and Expansion & Market flexibility.

De Toni and Tonchia (1998) contributed to the activity of conceptual systemization of the elder works on flexibility. Their work proposed a classification framework considering six main aspects of manufacturing flexibility, namely:

- definition of flexibility (in general and with particular reference to the production field);
- factors which determine the request for flexibility (variability of products and processes, internal and external environmental uncertainty);
- classification (dimensions) of flexibility (hierarchical, by phases, temporal, by object of variation, or based on a mixture of the previous dimensions);
- measurement of flexibility (direct, indirect and synthetic indicators);
- choice of determinant in obtaining flexibility (which can be distinguished in design or technological choices and organizational/managerial ones);

interpretation of flexibility (strategic vs. operational, defensive vs. offensive, potential vs. effective, etc.).

This framework was used to classify more than twenty years of research contributions on the topic. Among the various conclusions drawn by the authors, the subject of measurement of flexibility is seen as a field offering many opportunities for future research. Moreover, the authors examined in some detail the relationship between flexibility and company competencies. Latterly, they extended these ideas to propose a model for measuring manufacturing flexibility based on the characteristics of variation with which a process has to cope (De Toni and Tonchia 2002; De Toni and Tonchia 2003).

The contribution proposed by Zhang et al. (2003) described manufacturing flexibility as an integral component of value chain flexibility, and discussed its sub-dimensions. It also provided a research theoretical model linking flexible manufacturing competencies with volume flexibility and mix flexibility, and with customer satisfaction (Figure 3.2). An extensive literature review is carried out and the main concept of flexibility with its sub-dimensions is clarified including a recall to three distinctive attributes of flexibility: range, mobility and uniformity (Upton 1994). An analysis across a large number of organizations confirms empirically that flexible manufacturing competencies support the flexible capabilities of the firm, i.e. volume flexibility and mix flexibility, which in turn enhance customer satisfaction.

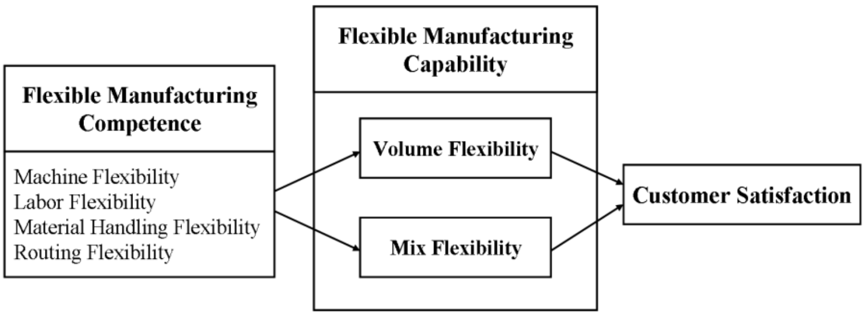

Fig. 3.2 Framework proposed by Zhang et al. (2003)

Shewchuk and Moodie (1998) provided a framework which is very different from the ones presented in the rest of the literature and aims at developing a means for both classifying existing flexibility definitions (or, as the author write, flexibility types and measures) and developing new definitions of flexibility, whether one needs to add some. The authors proposed a six-field hybrid classification framework which is then applied to map over 50 existing flexibility terms. This framework can be useful for having a first insight into the elementary components/dimensions of manufacturing flexibility, even if it does not fully address this issue. It also states that, in order to do this in a structured manner, one must start with suitable models and then derive the various flexibility types, based on the elementary components.

3.1.3 Design of Manufacturing Flexibility

The third group of works deals with approaches and models to implement flexibility forms during the system design phase. As anticipated, even if in literature many efforts are devoted to the analysis of flexibility, the link between the knowledge about flexibility and the design of the manufacturing systems is still weak at the moment. On the one hand, some authors consider the flexibility acquisition as a strategic option to react to frequent volume changes and evolutions of technological requirements of products. On the other hand, many works highlight the need to deeply analyze the risk associated to purchase high level of flexibility, taking into account the high involved investment (Stecke 1985; Matta et al. 2008).

Moreover, many examples can be considered concerning the relation between the level of flexibility embedded into the system and the system performance (Koren et al. 1999; Landers 2000). Kulatilaka and Marks (1988) developed an approach which proofs the disadvantages related to purchase flexibility in production contexts affected by limited uncertainty. Even though the strategic importance of flexibility is generally well recognized, it is not easy to assess the value of flexibility when trying to financially justify the investment in modern flexible manufacturing systems or in advanced manufacturing technologies in general. Discounted Cash Flow (DCF) techniques are inadequate for applications where the benefits are mainly strategic and not easily quantifiable in terms of cash flow. Generally, it happens that the value of investment in advanced manufacturing systems possessing flexibility is underestimated. Ramasesh and Jayakumar (1997) proposed a new approach to generate the Net Present Value (NPV) of a manufacturing system, considering that the need for flexibility in a manufacturing system arises from the stochastic (i.e. uncertain) and dynamic (i.e. evolving over time) nature of the internal and external environments. In fact, flexibility refers to the ability of the system to cope with the instability induced by the environment where the system operates. Bordoloi et al. (1999) developed a capacity expansion model by which an economical evaluation is accomplished to support the importance of flexibility and adaptability concepts for manufacturing systems. The decision about when to buy flexibility is related to the risk analysis of investments (Kahyaoglu 2002); in fact, flexible capacity is expensive and, indeed, the strategy to design high level of flexibility with uncertain information could involve significant costs. While many decision models deal with expected values of uncertain costs or profits, the reduced time span calls for proper risk management.

Even if there are actually many risk factors in system management, a recent tendency in logistics is the increased use of concepts borrowed from finance such as the quantile-based risk measure, i.e. Conditional Value-at-Risk (Bradimante and Mottola 2007).

Economical considerations regarding the flexibility gap - i.e. the gap between the level of actual flexibility and that required by the environment - are stressed by Llorens et al. (2005). Following this perspective, other works related to the corporate finance area can be mentioned (Kulatilaka 1988; Hodder and Triantis 1990; Trigeorgis 1996). They consider the flexibility notion as a financial option which can economically modify the company reaction to market not forecasted changes.

ElMaraghy (2005) linked the concept of manufacturing system life-cycle to manufacturing systems flexibility and reconfigurability. The author introduced the most recent views of a panel of experts from academia and industry on the comparisons between flexible and reconfigurable manufacturing (Terkaj et al. 2008). A thorough comparison between FMS and RMS paradigms is also presented, and finally the concepts of flexibility and reconfigurability are treated considering the wider concept of changeability.

Papers addressing the design of Focused Flexibility Manufacturing Systems (FFMSs) can be mentioned as well (Tolio and Valente 2006; Tolio and Valente 2007; Tolio and Valente 2008). The methods presented in these papers will be analyzed furthermore within Chapter 7 of this book.

3.1.4 Ontology on Flexibility

A considerable research effort has been devoted to the definition of different forms of flexibility to describe the characteristics of a manufacturing system. On the one hand, a given form of flexibility is considered as the capability of reacting to a well defined type of "stimulus" which can be experienced by the manufacturing system. On the other hand, a given form of flexibility may support various proactive strategies of the firm. Since the stimuli acting on the firm and the proactive strategies of the firm may differ, there is a need of various forms of flexibility. The result is that the number of flexibility types proposed in literature is really high even if some rationalization has been done. Other issues concern the ambiguous meaning of such flexibility form definitions and also the ambiguity among flexibility forms and other concepts (e.g. Expansion Flexibility vs. Reconfigurability).

This situation cannot be overcome since a given form of flexibility is an answer to a very specific problem and the uncountable number of existing problems leads to uncountable flexibility forms. Terkaj et al. (2008) have addressed this problem proposing an ontology on flexibility which aims at both classifying flexibility definitions and leading the system design process by providing a structured framework for manufacturing flexibility. The work of the authors starts from the consideration that each form of flexibility (e.g. Mix Flexibility, Routing Flexibility, etc.) is a *Compound Flexibility Form* and can be interpreted as a recipe to tackle a specific production problem by combining some *Basic Flexibility Forms* (Figure 3.3). Each *Basic Flexibility Form* is defined as the aggregation of two key concepts: *Dimensions* and *Levels*.

Basic Flexibility Dimensions are generally theoretical concepts that should not find a direct implementation and should not be measured. These *dimensions* are embedded in the various forms of flexibility which can be found in specific applications. A set of four *basic flexibility dimensions* have been proposed as reported in Table 3.1. This set respects the property of "orthogonality", i.e. all *dimensions* in the set are independent and one *dimension* cannot be obtained as a combination of the other ones. Also completeness property is satisfied, i.e. each form of flexibility can be derived as a specific combination of the given *dimensions*, as it will be shown in Sect. 3.2.

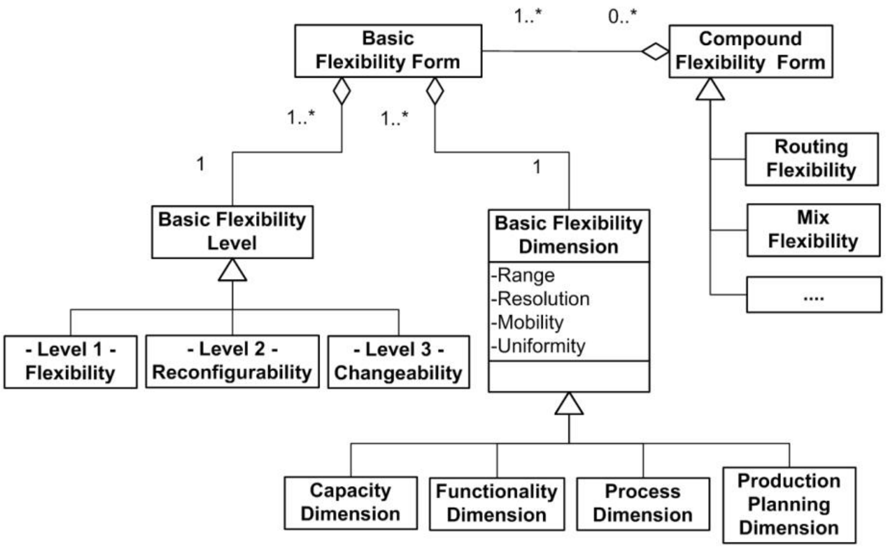

Fig. 3.3 Ontology on Flexibility (Terkaj et al. 2008)

Table 3.1 Basic Flexibility Dimensions (Terkaj et al. 2008)

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

Each *Basic Flexibility Dimension* is further specified by four attributes: Range, Uniformity, Mobility and Resolution (Table 3.2). The first three attributes were defined by Upton (1994), while Resolution attribute has been added by the authors of the ontology. Attributes are treated at a conceptual level, without aiming at developing a metric. The key idea is that the concepts contained in the dimensions cannot be completely defined if the attributes are not introduced.

Table 3.2 Flexibility Attributes

Attribute	Definition
Range	Extension of the differences among the various ways of behaving 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 things which can be done by the system.
Mobility	Mobility within the range. It expresses the ease with which it is possible to modify the behaviour 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 in the space. For instance, in the Functionality dimension it may represent how easily it can move from doing one thing to performing another one.
Uniformity	Uniformity within the range. It 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 doing different things.
Resolution	Resolution expresses how close the alternatives are 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 short the distance is between similar but differnt thing which can be done by the system.

The last concept proposed in the ontology on flexibility is the definition of *Basic Flexibility Levels*. These levels are related to real implementation of various forms of flexibility in the manufacturing system. For instance, a given *basic flexibility dimension* specified by its attributes may be present in a given system or it can be acquired if it is absent. In the second case, the system is one step behind compared to the first case, because of the need to take some actions to obtain the same capability. However, the fact that these actions can be taken means that the system has a predisposition making it different from a system which cannot be modified. This predisposition is normally called in the literature “Reconfigurability” (Koren et al. 1999).

The fact that a system is one step behind under a given dimension suggests the concept of “Level”. 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 proposed by Terkaj et al. (2008) are defined in Table 3.3. Through the definition of *basic flexibility levels*, the proposed ontology allows to unify the concepts of Flexibility, Reconfigurability and Changeability (Wiendahl et al. 2007). All these concepts deal with modifications in manufacturing systems and the difference among them consists in timing, cost and number of steps necessary to implement a modification.

Table 3.3 Basic Flexibility Levels (Terkaj et al. 2008)

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

The proposed ontology on flexibility is tested in this chapter carrying out two types of analysis. Firstly, possibility to map all the forms of flexibility described in the existing literature through the *basic dimensions* and *levels* is investigated in Sect. 3.2. Secondly, the attention is focused on the forms of flexibility in industrial production contexts within Sect. 3.3.

3.2 State of the Art Analysis

The *Compound Flexibility Forms* defined in the literature have been mapped according to the ontology proposed by Terkaj et al. (2008). Globally, 24 papers have been analyzed and 109 forms of flexibility have been found. The complete analysis is shown in Table 3.4; the *Compound Flexibility Forms* have been mapped defining which *Basic Flexibility Dimensions* are involved and at which Basic Flexibility Levels. The fields of the table stand respectively for the referenced paper (“Paper”), the name of the mapped *Flexibility Form* (“Compound Flexibility Form”) and the name of the *Basic Flexibility Dimensions*: Capacity (“Cap”), Functionality (“Func”), Process (“Proc”), Production Planning (“Plan”). If a basic flexibility dimension is necessary to define a flexibility form, then the cell in the respective column is filled in with the related *Basic Flexibility*

Level(s). For instance, Agility Flexibility as defined by Lee (1998) corresponds to Functionality Flexibility at Level 1.

An analysis of the *basic flexibility dimensions* embedded in the different *compound flexibility forms* shows that:

- 71.56 % of the forms is characterized by Functionality flexibility;
- 23.85 % of the forms is characterized by Capacity flexibility;
- 27.52 % of the forms is characterized by Production Planning flexibility;
- 9.17 % of the forms is characterized by Process flexibility.

The literature mapping highlights the presence of a high variety of definitions concerning each form of flexibility: even if in most of the cases these definitions are quite similar in the content (e.g. twelve definitions of Volume Flexibility), the diversity in some definitions derives from the fact that each type of stimulus requires an appropriate form of flexibility. Another consideration coming from the literature classification is that some forms of flexibility are very simple since they are concentrated on a small number of *dimensions* and sometimes they coincide with a basic *flexibility form* (e.g. Machine Flexibility), while other *flexibility forms* (e.g. Mix Flexibility) are rather complex and include different *dimensions*. For these compound forms of flexibility it is therefore common to find variations which are rather difficult to compare without using the dimensions and the levels.

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

Paper	Compound Flexibility Form	Cap	Func	Proc	Plan
(Lee 1998)	Agility	-	Level 1	-	-
(Gerwin 1993)	Change-over	-	Level 1	-	-
(Grubbstrom and Olhanger 1997)	Change-over	-	Level 1, Level 2, Level 3	-	-
(Kara et al. 2002)	Change-over	-	Level 1	-	-
(Pagell and Krause 2004)	Change-over	-	Level 1	-	-
(ElMaraghy 2005)	Control program	-	Level 1		Level 1
(Sethi and Sethi 1990)	Program	Level 1	Level 1	-	Level 1
(Gupta and Somers 1996)	Program	-	Level 1	-	Level 1
(Pagell and Krause 2004)	Delivery	-	-	-	Level 1
(Sethi and Sethi 1990)	Expansion	Level 2, Level 3	Level 2, Level 3	-	-
(Bordoloi 1999)	Expansion	Level 2, Level 3	Level 2, Level 3	-	-
(Parker and Wirth 1999)	Expansion	Level 2, Level 3	-	-	-

Paper	Compound Flexibility Form	Cap	Func	Proc	Plan
(Kara et al. 2002)	Expansion	Level 2, Level 3	Level 2, Level 3	-	-
(ElMaraghy 2005)	Expansion	Level 2	Level 2	-	-
(Gupta and Somers 1996)	Expansion and market	Level 2, Level 3	Level 2, Level 3	-	-
(Ramasesh and Jayakumar 1997)	Modification & Expansion	Level 2, Level 3	Level 2, Level 3	-	-
(Gerwin 1993)	Modification	-	Level 1	-	-
(Kara et al. 2002)	Modification	-	Level 1	-	-
(Pagell and Krause 2004)	Modification	-	Level 1	-	-
(Spicer 2005)	Scalability	Level 2	-	-	-
(Kara et al. 2002)	Input	-	Level 1	-	-
(Kara et al. 2002)	Job	-	Level 1, Level 2	-	Level 1
(Kara et al. 2002)	Job Shop Layout	Level 1	Level 1	-	Level 1
(Kara et al. 2002)	Launch	-	Level 1	-	-
(Zhang et al. 2003)	Labor	-	Level 1	-	-
(Grubbstrom and Olhanger 1997)	Work Force	-	Level 1, Level 2	-	-
(Ramasesh and Jayakumar 1997)	Machine and Labor	-	-	Level 1	-
(Sethi and Sethi 1990)	Machine	-	Level 1	-	-
(Gupta and Somers 1996)	Machine	-	Level 1	-	-
(Kochikar and Narendran 1998)	Machine	-	Level 1	-	-
(Parker and Wirth 1999)	Machine	-	Level 1	-	-
(Kara et al. 2002)	Machine	-	Level 1	-	-
(Zhang et al. 2003)	Machine	-	Level 1	-	-
(ElMaraghy 2006)	Machine	-	Level 1	-	-
(Gerwin 1993)	Material	-	-	Level 1	-
(Kara et al. 2002)	Material	-	Level 1	Level 1	-
(Sethi and Sethi 1990)	Material-Handling	-	Level 1	-	-
(Gupta and Somers 1996)	Material-handling	-	Level 1	-	-
(Kochikar and Narendran 1998)	Material-handling	-	Level 1	-	-
(Kara et al. 2002)	Material-handling	-	Level 1	-	-
(Zhang et al. 2003)	Material-handling	-	Level 1	-	-
(ElMaraghy 2006)	Material-handling	-	Level 1	-	-
(Grubbstrom and Olhanger 1997)	Product Mix	-	Level 1, Level 2	-	-
(Ramasesh and Jayakumar 1997)	Product Mix	-	Level 1	-	-

Paper	Compound Flexibility Form	Cap	Func	Proc	Plan
(Chen et al. 2002)	Product Mix	-	Level 1	-	-
(Gerwin 1993)	Mix	-	Level 1	-	-
(Perrone and Noto La Diega 1996)	Mix	-	Level 1	-	Level 1
(Li and Tirupati 1997)	Mix	Level 1	Level 1	-	Level 1
(Bateman et al. 1999)	Mix	-	Level 1	-	-
(Shewchuk and Moodie 2000)	Mix	-	Level 1	-	-
(Kara et al. 2002)	Mix	-	Level 1	-	-
(Liberopoulos 2002)	Mix (Production Capacity)	Level 1	Level 1	-	Level 1
(Zhang et al. 2003)	Mix	-	Level 1	-	-
(Pagell and Krause 2004)	Mix	-	Level 1	-	-
(Bateman et al. 1999)	Mix Range	-	Level 1	-	-
(Bateman et al. 1999)	Mix Response	-	Level 1	-	Level 1
(Van Hop 2004)	Mix Response	-	Level 1	-	Level 1
(Kara et al. 2002)	Mobility	-	Level 1	-	Level 1
(Sethi and Sethi 1990)	Operations	-	-	Level 1	-
(Parker and Wirth 1999)	Operation	-	-	-	Level 1
(Kara et al. 2002)	Operation	-	-	-	Level 1
(ElMaraghy 2006)	Operation	-	-	Level 1	Level 1
(Sethi and Sethi 1990)	Routing	-	-	Level 1	Level 1
(Gerwin 1993)	Routing	-	-	Level 1	Level 1
(Gupta and Somers 1996)	Routing	-	-	-	Level 1
(Kochikar and Narendran 1998)	Routing	-	-	-	Level 1
(Parker and Wirth 1999)	Routing	-	-	-	Level 1
(Kara et al. 2002)	Routing	-	-	-	Level 1
(Zhang et al. 2003)	Routing	-	-	-	Level 1
(ElMaraghy 2006)	Routing	-	-	-	Level 1
(Kara et al. 2002)	Sequencing	-	-	-	Level 1
(Kara et al. 2002)	Pallet Fixture	-	Level 1	-	Level 1
(Kara et al. 2002)	Parts	-	Level 1	-	-
(Sethi and Sethi 1990)	Process	-	Level 1	-	-
(Gupta and Somers 1996)	Process	-	Level 1	-	-
(Parker and Wirth 1999)	Process	-	Level 1	-	-
(Kara et al. 2002)	Process	-	Level 1	Level 1	Level 1
(ElMaraghy 2006)	Process	-	Level 1	-	-
(Gupta and Somers 1996)	Product and production	-	Level 1	-	Level 1

Paper	Compound Flexibility Form	Cap	Func	Proc	Plan
(Sethi and Sethi 1990)	Product	-	Level 2	-	-
(Kara et al. 2002)	Product	-	Level 1	-	Level 1
(Parker and Wirth 1999)	Product	-	Level 1	-	-
(Shewchuk and Moodie 2000)	Product	-	Level 1	-	-
(ElMaraghy 2006)	Product	-	Level 1	-	-
(Sethi and Sethi 1990)	Production	-	Level 2	-	-
(Kara et al. 2002)	Production	-	Level 1	-	-
(Parker and Wirth 1999)	Production	-	Level 1	-	-
(Shewchuk and Moodie 2000)	Production	-	Level 1	-	Level 1
(ElMaraghy 2006)	Production	-	Level 1	-	-
(Perrone and Noto La Diega 1996)	Production	-	Level 1	-	-
(Kara et al. 2002)	Range	-	Level 2	-	-
(Seifoddini and Djassemi 1997)	Range	-	Level 1	-	-
(Kara et al. 2002)	Response	Level 2	Level 2	-	-
(Kara et al. 2002)	Short Term	-	Level 1	-	-
(Correa and Slack 1996)	System Robustness	-	-	Level 1	Level 1
(Kara et al. 2002)	Tactical	Level 1	Level 1	-	-
(Kara et al. 2002)	Technological	-	Level 1, Level 2	-	-
(Sethi and Sethi 1990)	Volume	Level 1	-	-	-
(Gerwin 1993)	Volume	Level 1	-	-	-
(Khouja 1995)	Volume	Level 1	-	-	-
(Gupta and Somers 1996)	Volume	Level 1	-	-	-
(Grubbstrom and Olhanger 1997)	Volume	Level 1, Level 2, Level 3	-	-	-
(Ramasesh and Jayakumar 1997)	Volume	Level 1	-	-	-
(Parker and Wirth 1999)	Volume	Level 1	-	-	-
(Shewchuk and Moodie 2000)	Volume	Level 1	-	-	-
(Kara et al. 2002)	Volume	Level 1	-	-	-
(Zhang et al. 2003)	Volume	Level 1	-	-	-
(Pagell and Krause 2004)	Volume	Level 1	-	-	-
(ElMaraghy 2006)	Volume	Level 1	-	-	-

3.3 Analysis of Real Systems

The ontology on flexibility (Terkaj et al. 2008) has been used to analyze some real production systems as well. The goal was to verify whether the requirements of flexibility addressed by these systems could be described by flexibility *dimensions* and *levels*. Therefore, in the following sub-section an industrial case is analyzed according to the ontology; other examples of industrial case analysis can be found in the paper by Terkaj et al. (2008).

3.3.1 Mori Seiki Case

Mori Seiki, one of the biggest Japanese producers of machine tools, proposes to its customers a range of solutions to face the increasing requirement of production system changes due to shorter and shorter product life-cycles. In particular, the production of components for the automotive market highlights two problems: the choice of the size of the machines and the need of frequently reconverting the machines and the line configuration due to changes in the specifications of the products.

The problem connected to the size of machines is huge and still relevant. In fact, big flexible machines are often characterized by relevant structure vibrations, high thermal distortions and other structural problems that make the meeting of quality specifications extremely expensive. To achieve highly stable and accurate machine tool operation over long operating periods, the complicated motion mechanism of versatile machine tool system should be simplified, avoiding indirect driving schemes as much as possible. For instance, Fujishima and Mori (2007; 2008) have proposed a Direct Drive motor solution to build high speed and high precision rotary axes. Moreover, in the past machines have been designed with a high degree of flexibility in order to process products of variable size. However, processed workpieces are usually small. Therefore, it is necessary to design the right degree of flexibility to process different product variants within the same system, but also to provide high capability to meet the strict product specifications imposed by the market.

With this aim, Mori Seiki started the production of small, modular and flexible machines that can be integrated in reconfigurable lines. Machines of the NX series (Figure 3.4) are machining centers designed for mass production applications.

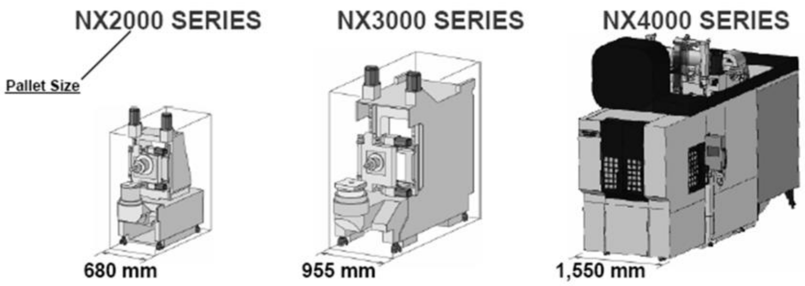

Fig. 3.4 Mori Seiki Machines of the NX series (Courtesy of Mori Seiki)

For example, machine NX3000 is endowed with a series of technical solutions which can be used to change the machine configuration. It has a structure which rapidly allows to pass from a 2-axis configuration to a 3-axis configuration and from a vertical to an horizontal configuration. Some structural characteristics have been introduced in order to make the machine more stable (e.g. the slides for the vertical motion are heavier in order to reduce vibrations). The low vibration together with the small size of the production modules allows higher precision in the operation. Moreover, the small size allows to reduce the thermal distortion. The advantage of smaller machines consists of high precision, high speed and efficiency as well as high accessibility to the workpieces, to the table and to the machine body. This means a reduction in the number of setups together with reduced time for maintenance of the machining units and an efficient chip disposal system.

The reduced machine size has a positive impact also on the performance at a system level because it allows to design a more compact system layout which leads to shorter travel distances for transfer shuttles, lower number of robots for load/unload operations and a reduced floor space need. Two examples of system layout are shown in Figures 3.5 and 3.6.

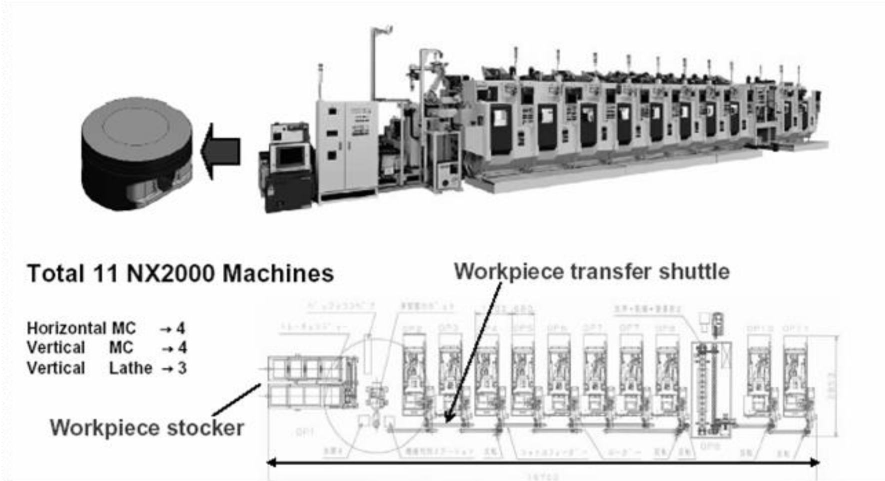

Fig. 3.5 Impact of small machines at a system level – Travel distance is reduced by 30% compared to previous models (Courtesy of Mori Seiki)

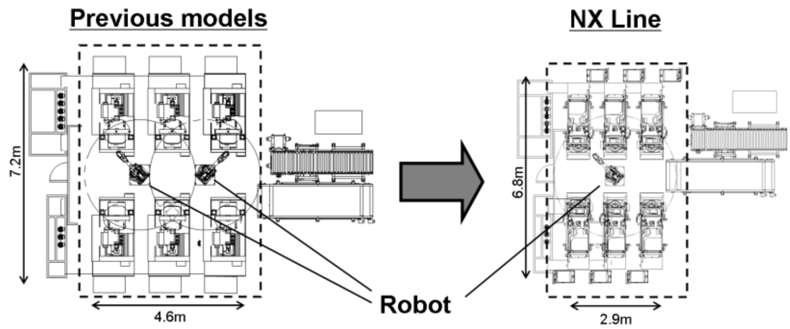

Fig. 3.6 Impact of small machines at a system level – Floor space is reduced (Courtesy of Mori Seiki)

As it can be noticed from the description of the Mori Seiki case, a focused flexibility solution is proposed to reduce the waste deriving from the development of machines with excess flexibility when compared to the real needs of the customers. Mori Seiki machines are provided with Capacity, Functionality, Process and Production Planning Flexibility. Capacity flexibility is given by the modularity of machines. In fact, being modular and highly interoperable, machines can be added or removed from a production line according to the current demand (Figure 3.7). Removed machines can be eventually used as stand alone machines to accomplish different tasks, or can be organized in different lines. Therefore the system is characterized by Capacity flexibility at Level 2.

Functionality flexibility is provided at a machine level thanks to the ability of processing parts in the 2- or 3-axis configurations and in the horizontal or vertical configurations. Moreover, Functionality flexibility can be provided at a system level by introducing new modules with different characteristics. These properties can be used to process different product types. Therefore, Functionality flexibility is provided both at Level 1 and Level 2.

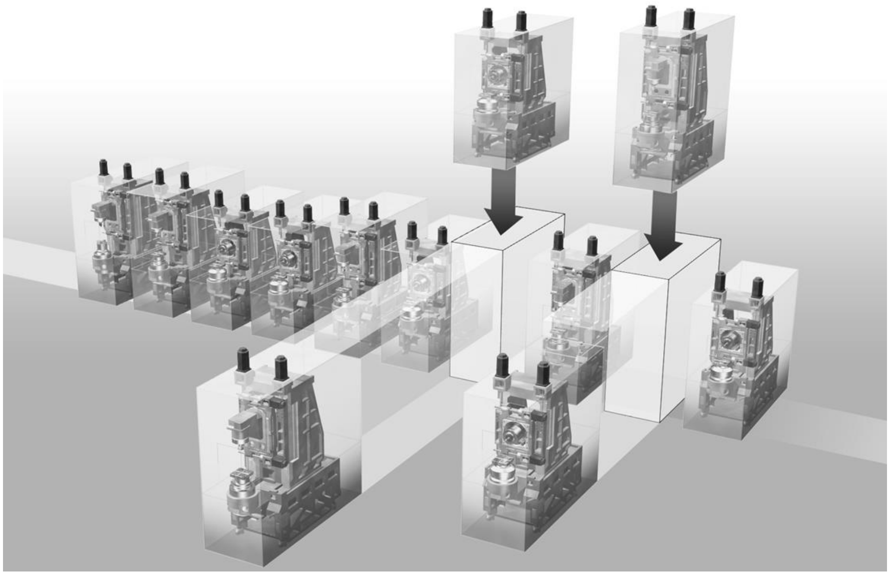

Fig. 3.7 Capacity flexibility through modularity (Courtesy of Mori Seiki)

The characteristics of the system can be also used to process the same part type with different machine/system configurations. In this sense, the system is endowed with Process flexibility at Level 1 and 2. Finally, the manufacturing system type proposed by Mori Seiki allows also Production Planning flexibility at Level 1, since it is possible to easily change the assignment of the operations to the machines.

The analysis of the technological solution offered by Mori Seiki according to the ontology on flexibility is summarized in Table 3.5.

Table 3.5 Mori Seiki case flexibility analysis

Capacity Flexibility	Functionality Flexibility	Process Flexibility	Production Planning Flexibility
Level 2	Level 1, Level 2	Level 1, Level 2	Level1

The manufacturing systems offered by Mori Seiki are a clear example of systems with Focused Flexibility. The focalization is due to the adoption of machining centers with a small work cube. Moreover, it is not required to adopt only general purpose machining centers; in fact, it is possible to acquire different machine modules to answer to different production requirements, thus tailoring the solution to the set of products.

3.4 Conclusions

The introduction of Focused flexibility may represent an important means to rationalize the way by which flexibility is embedded in manufacturing systems. In this sense, it is necessary to have a deep understanding of the nature of flexibility as well as to clearly define the dimensions of flexibility. The developed analysis has been supported by accomplishing an extensive literature review and by adopting an innovative ontology on flexibility. Resulting evaluations emphasize the first findings of the empirical research developed in Chapter 2. Firstly, the production problems analysis, even in an evolutionary perspective, represents a very critical task for companies. Making mistakes in production evaluation and forecasts can have strong impacts on the system design. Secondly, the presence in the literature of many formalization frameworks to classify and measure flexibility forms could contribute to make the decision maker get confused instead of supporting him/her over the system design process. In order to address this problem the current chapter has proposed a framework to systemize and clarify some important past research efforts. The same framework can also be used to support the design of new systems as suggested by Terkaj et al. (2008).

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