Design of Flexible Production Systems
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Methodologies and Tools
Manufacturing Flexibility is usually considered as the main answer for surviving in present markets characterized by short lead times, tight product tolerances, pressure on costs, frequent changes in demand and continuous evolution of the technological requirements of the products. Even if flexibility can be seen on the one hand as an important strategic option, on the other hand one must consider that the competitiveness of a firm can be strongly affected by the burden of capital intensive investments in system flexibility. Therefore there is the need of viewing system flexibility in the global picture trying to consider both the advantages and the disadvantages related to the acquisition of flexibility.

In particular production contexts characterized by mid to high demand volume of well identified families of products in continuous evolution do not require the highest level of flexibility; therefore, manufacturing system flexibility can be rationalized by finding out the best trade-off between productivity and flexibility. Manufacturing systems endowed with the right level of flexibility required by the production problems are named within the book Focused Flexibility Manufacturing Systems – FFMSs. A great deal of industrial sectors have to face this trade-off including, among the others, automotive, white goods, electrical and electronic goods. Also, the introduction of focused flexibility is not only important for system users but also for machine tool builders whose competitive advantage is based on the ability of customizing their system solutions on the basis of the needs of their customers.

However, designing manufacturing systems that optimally satisfy the production requirements represents a very complex problem. Aspects ranging from manufacturing strategy to risk appraisal and management techniques, and from scenario analysis to system performance evaluation must be jointly taken into account considering the whole system life-cycle. Moreover, traditional system architectures do not always represent the most efficient solutions to properly face the new production context. Indeed, dedicated systems are not able to adapt to changes of the product characteristics while flexible systems often offer more flexibility than what is really needed, thus increasing investment and operating costs. The required level of system flexibility impacts on the architecture of the system and the explicit design of flexibility.
can lead to new hybrid systems, i.e. automated integrated systems where the products can be processed both by general purpose machines and by dedicated machines. This is a key issue of FFMSs and results from the matching of flexibility and productivity that characterize Flexible Manufacturing Systems (FMSs) and Dedicated Manufacturing Systems (DMSs), respectively.

Therefore the mission of the book is: “to define methodologies and tools to design production systems endowed with the right level of flexibility needed to face, during their life-cycle, the evolution of products, processes and market demand”. The underlying idea is that flexibility has a cost therefore by using the right level required by the production problem on hand it is possible to find the optimal trade-off between flexibility and productivity.

In spite of the relevance of the production system design topics, existing methodologies and tools do not provide an extensive support to the system designer since they typically deal with sub-problems of the whole design process. Indeed the wideness the topics related to system design can be seen as one of the reasons why this problem has not been sufficiently addressed until now. This work can be considered as an effort to provide an integrated framework to support the design of manufacturing systems that are able to cope with present and forecasted production problems in a cost-effective way. Herein, the main phases of the design activity are jointly structured, starting from the data collection and formalization of production information till the design and performance evaluation of the optimal system solution. Even if the proposed design approach can be applied to different production contexts and different system architectures, the authors have focused the analysis on the design of FFMSs. All the steps of the proposed approach are deeply investigated, and particular attention is paid to the methodologies adopted to face the different sub-problems (including: mathematical programming, stochastic programming, reverse kinematics and simulation techniques). By approaching the various aspects related to the design of system flexibility with formalized techniques and by applying the proposed framework to a set of real and realistic cases it is possible to have some figures of the advantages and costs related to flexibility. These figures even if related to the specific cases considered can provide interesting insights in the pros and cons of flexibility which can be exploited at managerial level.

Most of the methodologies presented in this book have been developed within the two-year project “Methodologies and tools for the configuration of production systems with focused flexibility” funded by the Italian Ministry of University and Research (MUR) and coordinated by Politecnico di Milano – Dipartimento di Meccanica. The project itself is a joint effort of Politecnico di Milano, Politecnico di Torino, Università di Palermo, Università di Catania e Università del Salento. This book is also the result of continuous interactions with suppliers and users of manufacturing systems and in particular, among the others, with MCM S.p.A., Ferraioli & C. S.r.l. Nuova Meccanica S.p.A.

The book structure follows the framework that has been developed to address the system design problem. This framework is both broad and
detailed, since it pays attention to all the relevant levels of an organization that are involved in the system design activity (see Chap. 1). Moreover, the framework models both the point of view of the machine tool builder and the point of view of the system user.

The work presented in this book links together different research fields by means of a shared information formalization (see Chap. 4). The research fields consist of: Manufacturing Strategy (see Chap. 5), Process Planning (see Chap. 6), System Design (see Chap. 7), Capacity Planning (see Chap. 8) and Performance Evaluation (see Chap. 9); moreover, the book gives a contribution to the formalization and rationalization of the concepts related to manufacturing system flexibility (see Chap. 3). The attention to industrial issues is confirmed by empirical studies (see Chap. 2) and real case analyses (see Chap. 10) which are presented within the book chapters to define the production domain where FFMSs are more profitable than traditional system architectures. Finally, some conclusions regarding new machine architectures are proposed to machine tool builders willing to provide innovative system solutions.

As it can be seen from this brief preface, this book is only a step in a very complex and wide field, and it is an attempt, with limits and open issues, to have a joint understanding of system related issues that are frequently dealt separately. Indeed, the interactions among these issues deeply affects the resulting system flexibility and productivity; the comprehension and formalization of these interactions is the key to be able to design systems whose evolution is tuned on the evolution of the processes they implement and the product families they produce.

Milano, Italy

Tullio Tolio
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**Abbreviations**

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<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AMS</td>
<td>Automated Manufacturing System</td>
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<tr>
<td>BoM</td>
<td>Bill of Material</td>
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<td>CV</td>
<td>Coefficient of Variation</td>
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<td>CAFD</td>
<td>Computer Aided Fixture Design</td>
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<td>CAPP</td>
<td>Computer Aided Process Planning</td>
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<td>CNC</td>
<td>Computer Numerical Control</td>
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<td>DFD</td>
<td>Data Flow Diagram</td>
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<td>DSS</td>
<td>Decision Support System</td>
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<td>DMS</td>
<td>Dedicated Manufacturing System</td>
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<td>DCF</td>
<td>Discounted Cash Flow</td>
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<td>FIFO</td>
<td>First In First Out</td>
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<td>FCI</td>
<td>Fixture Capacity Index</td>
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<td>FMS</td>
<td>Flexible Manufacturing System</td>
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<td>FFMS</td>
<td>Focused Flexibility Manufacturing System</td>
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<td>GA</td>
<td>Genetic Algorithm</td>
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<td>MUR</td>
<td>Italian Ministry for University and Research</td>
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<td>LCA</td>
<td>Life-Cycle Analysis</td>
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<td>MS</td>
<td>Manufacturing Strategy</td>
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<td>MRD</td>
<td>Mapping Requirements on Devices</td>
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<td>MHS</td>
<td>Material Handling System</td>
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<td>NPV</td>
<td>Net Present Value</td>
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<td>OMT</td>
<td>Object Modeling Technique</td>
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<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<td>PC</td>
<td>Pallet Configuration</td>
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<td>PM-FMS</td>
<td>Parallel Machine-FMS</td>
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<td>PM</td>
<td>Performance Matrix</td>
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<td>PSL</td>
<td>Process Specification Language</td>
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<td>ROA</td>
<td>Real Options Analysis</td>
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<td>RMT</td>
<td>Reconfigurable Machine Tool</td>
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<td>RMS</td>
<td>Reconfigurable Manufacturing System</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>RTL</td>
<td>Rigid Transfer Lines</td>
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<td>SFC</td>
<td>Setup Face Configuration</td>
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<td>SME</td>
<td>Small and Medium Enterprise</td>
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<td>SPD</td>
<td>Standard Placement Direction</td>
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<td>STD</td>
<td>State Transition Diagram</td>
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<td>SM</td>
<td>Switching Costs Matrix</td>
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<td>TAD</td>
<td>Tool Approach Direction</td>
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<td>UML</td>
<td>Unified Modeling Language</td>
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<td>VRL-KCiP</td>
<td>Virtual Research Lab for a Knowledge Community in Production</td>
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<td>WS</td>
<td>Workingstep</td>
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Abstract  Manufacturing Flexibility is seen as the main answer for surviving in markets characterized by frequent volume changes and evolutions of the technological requirements of products. However, the competitiveness of a firm can be strongly affected by capital intensive investments in system flexibility. This chapter presents an approach to design new manufacturing system architectures endowed with the right level of flexibility required by the specific production problem. These systems are named Focused Flexibility Manufacturing Systems (FFMSs). The key idea consists in tuning system flexibility on the production problem to cope with uncertainty related to the evolution of product demand. The significance of this topic and its potential impact on the industrial sector in the medium-long run is testified by the interest shown by companies making initial efforts in this field.

Keywords  Manufacturing system design activities  .  Focused Flexibility Manufacturing Systems – FFMS

1.1 Market Uncertainty and Manufacturing Flexibility

Manufacturing companies have to cope with the increasing pressure from global marketplace. In the last decade, the production of mechanical components to be assembled in final products produced in high volumes (e.g. cars, mopeds, industrial vehicles, etc.) has undergone deep changes due to the overall modifications in the way companies compete. In this situation the following trends can be observed:

- Strategic components tend to be manufactured by the companies that produce the final products. For these strategic components firms define long
term plans. As a consequence, the technological characteristics, even if in continuous evolution, can be predicted with good accuracy.

- Less critical components tend to be externalized. In a context of continuous cost reduction, the producers of components try to obtain economies of scale by enlarging their size while specializing on some types of components.

In both cases companies work on quite stable product categories produced in high volumes but, at the same time, they must cope with frequent product modifications and short product life-cycles. These drivers force the manufacturers to evaluate the ability to change their manufacturing systems and the penalty related to the change (Matta et al. 2005). This represents a complex issue in dynamic manufacturing contexts (Beach et al. 2000) like automotive, semiconductor, electronics and high tech markets, because the products are affected by frequent changes in volumes and technologies.

It results that critical factors needed to be competitive are: short lead time, high quality of products, reactivity to market frequent changes and cost-effective production (Wiendahl et al. 2007). Obtaining optimality in each of the listed objectives can be difficult: frequently it happens that reaching optimal values for a single factor reduces the possibility of reaching optimal values for the other ones. This is the reason why companies often define production objectives as trade-offs among these critical factors (Chryssolouris 1996).

Moreover, information related to production changes is often uncertain and the decision maker could be not able to precisely evaluate the probabilities associated with alternative production options. As a consequence, production system design activities can be highly complex and risky.

In this context the acquisition of production capacity is particularly difficult (Matta and Semeraro 2005). Indeed, on the one hand dedicated manufacturing systems are not adequate to accommodate continuous product changes, even if they are competitive from the point of view of costs. On the other hand, flexible manufacturing systems have excessive flexibility which often remains unused and has a negative impact on costs. It results that manufacturing flexibility is not always a desirable characteristic of a system and in some cases it can jeopardize the profitability of the firm.

Manufacturing flexibility has a strategic role for firms that want to compete in a reactive or a proactive way (Cantamessa and Capello 2007; Terkaj et al. 2008). In fact, the ability of designing production systems whose flexibility degree is customized on the present production problem and, at the same time, it takes into account future product evolutions, can lead to a competitive advantage. In the following section, some examples provided by recent literature will be presented to support the analysis of manufacturing flexibility.

From the scientific perspective, focusing the flexibility of a production system on the specific needs represents a challenging problem. Indeed, the customization of system flexibility provides economic 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 allow decoupling the various phases of manufacturing system design.

Therefore, manufacturing system flexibility must be rationalized and it is necessary to find out the best trade-off between productivity and flexibility by designing manufacturing systems endowed with the right level of flexibility required by the production problem (Ganzi and Tolio 2003). This new class of production systems is named Focused Flexibility Manufacturing Systems – FFMSs (Tolio and Valente 2006). The design of FFMS flexibility degree calls for a very careful risk appraisal: to reach this goal all the activities ranging from the 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.

The introduction of focused flexibility would be particularly important for machine tool builders whose competitive advantage is based on the ability of customizing their products on the basis of needs of their customers (Cantamessa et al. 2007). This does not necessarily mean to design new machine concepts; indeed, customizing the production flexibility could simply imply to combine existing resources in an appropriate way, answering to production requirements. For instance, new devices can be integrated with old machines and/or a production system can be characterized by flexible machines served by a rigid transport belt. In fact, the key issue is that focusing the whole system flexibility on the production problem does not exactly correspond to selecting customized devices but it represents just one design option. Industrial efforts with this aim have been addressed by Terkaj et al. (2008).

To deeply understand how important is the strategic rationalization of flexibility, both from the academic and industrial perspectives, this chapter provides an extensive overview of this topic: a first analysis of the impact of production problem characteristics on the manufacturing flexibility degree required by production systems will be developed; afterwards, the new concept of Focused Flexibility Manufacturing Systems – FFMSs will be characterized in detail, highlighting the main differences with traditional production systems. Then, the FFMS design framework will be defined describing the main steps of the configuration phase; finally, the whole structure of the book will be illustrated.

1.2 The Impact of Production Problem Characteristics on Manufacturing System Flexibility

The previous section has highlighted the importance of considering production characteristics during the manufacturing system design phase. If a firm does not take into account production requirements during the system design phase, the
degree of manufacturing flexibility could result not appropriate for the problem.

In this section, the relation between production requirements and corresponding system architectures are investigated with reference to the state of the art. It is rather frequent to find in literature the description of industrial situations where flexible systems have unsatisfactory performance (Koren et al. 1999; Landers 2000), cases where available flexibility remains unused (Sethi and Sethi 1990; Matta et al. 2001), or cases where the management perceives flexibility more as an undesirable complication than a potential advantage for the firm (Stecke 1985). Kulatilaka and Marks (1988) show that, at strategic level, flexibility can even be detrimental under certain circumstances particularly when uncertainty can be limited by means of proper agreements and contracts.

Traditionally, rigid transfer lines (RTL) have been adopted for the production of a small family of part types required by the market in high volumes (Koren et al. 1998). RTLs are characterized by low scalability and therefore they are typically dimensioned on 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 full capacity. On the other hand, flexible manufacturing systems (FMSs) and parallel machine – FMSs (PM-FMSs) have been adopted to produce a large variety of parts in small quantities (Hutchinson and Pflughoeft 1994; Grieco et al. 2002) and they are are conceived to react to most of the possible product changes. The investment to acquire an FMS is very high and it considerably affects the cost to produce a part; indeed, its flexibility may be too high and expensive for the needs of a producer of components for the automotive industry (Sethi and Sethi 1990). The high financial and organizational impact of FMSs has reduced their diffusion in the past; indeed, the initial outlay is so high that it severely strains the financial resources of the firms.

Recent research efforts seem to individuate the concept of reconfigurability as the answer to the need for facing continuous changes in the production problems (Koren et al. 1999; Koren 2003, 2005, 2006). In fact, reconfigurability describes the operating ability of a production system or device to switch with minimal effort and delay to a particular family of work pieces or subassemblies through the addition or removal of functional elements (Wiendahl et al. 2007). In order to achieve exact flexibility in response to demand fluctuations, an RMS must be designed considering certain qualitative and quantitative enablers: modularity, integrability, customization, scalability, convertibility and diagnosability. However, despite the concept of reconfigurable resources is highly innovative it is quite difficult to be pursued considering available software and hardware technologies. Conversely, reconfigurability at system level can be obtained by using existing resources and production systems can be reconfigured every time the production problem requires it (Matta et al. 2008a). Unfortunately, this approach is not always cost-effective. Firstly, the reconfigurability option should be designed in order to accomplish its implementation when changes occur. Secondly, any reconfiguration along the system life-cycle
leads to face not only the installation costs but also operating costs related for instance to the ramp-up phase, typically characterized by machine malfunctioning and breakdowns, lost production and learning (Matta et al. 2008b).

1.3 Introduction to Focused Flexibility Manufacturing Systems – FFMSs

The introduction of focused flexibility may represent an important means to rationalize the way flexibility is embedded in manufacturing systems. In particular, traditional production system architectures could not represent the most profitable solutions in case of mid to high production volumes of well identified product families in continuous evolution.

Focused Flexibility Manufacturing Systems – FFMSs (Tolio and Valente 2006) represent a competitive answer to cope with the analyzed production context since they guarantee the optimal trade-off between productivity and flexibility. Moreover, the customization of system flexibility on specific production problems leads to the minimization of the system cost during its life-cycle. Indeed, the flexibility degree in FFMSs is related to their 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 flexibility and productivity that characterize FMSs and Dedicated Manufacturing Systems (DMSs), respectively. FFMSs are hybrid systems, in the sense that they can be composed both of general purpose and dedicated resources. This innovative architecture derives from the consideration that system flexibility is related both to the flexibility of each single selected resource and to the interaction among the resources which compose the system. For instance, a flexible system can be composed of dedicated machines and highly flexible carriers.

At first sight FFMSs could appear to be similar to Reconfigurable Manufacturing Systems (RMSs) (Koren et al. 1999; Ling et al. 1999; Landers 2000); the difference between these two classes of systems is in the timing of flexibility acquisition (Terkaç et al. 2008). Deciding about flexibility and reconfigurability means to consider two options. The first option deals with designing a dedicated system in which the reconfiguration option can be implemented in the future when production changes occur. This leads to design a system with the minimum level of flexibility required to cope with the present production problem. In this case FFMSs and RMSs have similar performance. The alternative option is to purchase more flexibility than the amount strictly required by the present production problem in order to avoid future system reconfigurations.
and ramp-ups. 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 production problems.

The choice between designing the reconfigurability option or acquiring extra-flexibility is strictly related to the investment costs analysis. For instance, if extra-flexibility costs are lower than the discounted value of reconfigurability costs and ramp-up costs, then a flexible solution can be more profitable.

Another fundamental issue to be considered is the industrial impact of the manufacturing flexibility rationalization. Even if current production contexts frequently present situations which would fit well with the FFMS philosophy, tradition and know-how of machine tool builders play a crucial role. Even if firms agree with the focused flexibility vision, nevertheless they often decide not to pay the risk and efforts related to the design of this new system architecture (Terkaj et al. 2008). The aspects which in the long run can convince the machine tool builders to provide innovative solutions to the customers depend on the profitability of FFMSs compared to FMSs and RMSs. At the moment, for different reasons and with more or less clear intents, many machine tool builders are trying to create new system architectures which to some extent represent first steps towards focusing the manufacturing flexibility. The introduction of focused flexibility would be particularly important for European machine tool builders whose competitive advantage is based on the ability of customizing their products on the basis of needs of their customers. To study the importance of the focused flexibility topic, an empirical research on the industrial viewpoint has been carried out. This analysis, presented in Chap. 2, gives a better understanding of the following key issues: (i) the value that firms assign to manufacturing flexibility; (ii) the approach adopted to tackle the demand of manufacturing flexibility; (iii) how the firms might react to the “focused flexibility” vision (Cantamessa and Capello 2007). Moreover, an example of industrial solutions related to focused flexibility will be presented in Chap. 3 (see Sect. 3.3.1).

1.4 Issues of the FFMS Design Phase

The configuration of Focused Flexibility Manufacturing Systems requires the integration of various aspects related to product and process to support the design of the production system life-cycle. The solution of this problem is based on a deep investigation of very different topics ranging from manufacturing strategy to risk appraisal and management techniques, and from system performance evaluation to scenario analysis. The wideness of these topics can be seen as one of the reasons why this problem has not been sufficiently addressed so far (Cantamessa et al. 2007).

The first key issue characterizing the FFMS design framework derives from the need for clarifying the relationship between the different types of flexibility
and the management and technical actions that must be followed to attain them. This lack of knowledge represents a critical problem for firm management since the definition of the proper course of actions to obtain and implement flexibility forms can be risky. Therefore, to fully understand the diffusion process of flexible automation and appreciate the problems it has encountered, it is necessary to investigate the choices made by companies. Thus, it is important to develop an empirical research on the adoption of flexible automation to study the value that firms assign to manufacturing flexibility. This analysis could contribute also to clarify how the firms not adopting FMSs have tackled the demand of manufacturing flexibility and how they might react to the “focused flexibility” approach.

A way to cope with the issues related to manufacturing system design is to define more precisely and in quantitative terms the required forms of flexibility. The importance and innovation of this topic is highlighted by recent contributions aiming at precisely identifying the required flexibility profiles (Gupta and Buzacott 1989; Upton 1994; Koste and Malhotra 1999). However, even if the goal of these works was to define the impact of flexibility in quantitative terms, the obtained results tend to be qualitative.

The research effort concerning this topic highlights an interesting consideration, i.e. the need for evaluating if the performance improvement justifies the extra-costs required by system flexibility. At the moment, this problem remains largely unsolved. Therefore, it results fundamental to find ways to express explicitly the flexibility needs of the firms starting from the analysis of the production problem. The key aspect of this approach is to be operative and pragmatic. Whereas, traditionally, existing design approaches start from the definition of the required flexibility levels, the framework presented in this chapter focuses the analysis on the production problem evaluation. Moreover, one has to consider that currently there is no standard methodology to define the characteristics of a production problem which takes into account the evolution over time: for this reason, it is necessary to define in a precise and formalized way the features of the problem, integrating models and visions coming from different fields.

The design of FFMSs addresses another critical issue. In fact, by reducing the flexibility levels of a system, the ability to cope with production variability is decreased. In this sense, the availability of flexibility in excess can sometimes prevent from some types of risk. As a consequence, in the definition of the right level of flexibility a key role is played by methodologies and tools to design the system flexibility considering the risks connected with the choice. The problem is complex because after that the required flexibility profiles have been defined, it is necessary to devise methodologies to design a system able to provide those levels of flexibility. This requires, on one side, the evaluation of the characteristics of different system architectures and of different machines and, on the other side, the correct matching between the required flexibility and the implemented system.
1.5 The Design of FFMSs

The previous section has highlighted the complexity of the FFMS design problem by focusing the analysis on the key issues which should be faced. This analysis represents the basis on which the FFMS design framework has been developed. However, despite herein the attention is centered on FFMSs, the proposed framework has more general applicability. Indeed, the provided system design framework starts from the production context analysis and implicitly defines the system flexibility requirements without considering existing flexibility taxonomies and classifications. Moreover, another key issue of the FFMSs design framework consists of considering at the same time two main actors involved in the system configuration problem: the System User and the Machine Tool Builder. The interactions between the actors are represented with a UML Activity Diagram in Fig. 1.1. The system user starts the information flow

![Fig. 1.1 System user and machine tool builder interaction](image-url)
sending a bid inquiry to one or more machine tool builders. Each machine tool builder carries out a preliminary assessment of bidding opportunity. If the potential order is interesting, then the machine tool builder designs a manufacturing system which satisfies the production requirements related to the types of product and the demand volumes defined by the client. System configuration requires as input a technological analysis of the production problem and this activity is usually executed by machine tool builders. When the system user receives the set of bids, it is possible to evaluate if the investment is cost effective. If it is effective, then an order is submitted to the winning machine tool builder who can start the production of the system.

Since there are two types of actor, the problem of system design and offer generation can be addressed according to the system user perspective or to the machine tool builder one. While in the former case the problem has been studied both technologically and economically, in the latter case there are few specific studies and mainly works addressing the problem of bid generation for a generic seller, without dealing with technological aspects.

The different knowledge and objective of the two actors in the problem can lead to designing manufacturing systems which are suboptimal for the needs of the user; this can happen when the user is wrong about his requirements forecasts, or because the machine tool builder has designed a system with excessive flexibility to cope with missing information from the client or because the machine tool builder succeeded in selling an oversized system. In the following section the system machine tool builder and system user perspectives will be illustrated.

## 1.5.1 Description of the FFMS Design Approach

As previously stated, a fundamental step of the FFMS design framework consists of a deep understanding of the information flow that characterizes the whole process. The definition of the information flow at industrial level is necessary to develop a unique standard conceptual reference framework for the formalization of data concerning products, processes and production systems and their relations, because these data play a key role within a system configuration architecture (Cantamessa et al. 2007).

An IDEF0 diagram has been developed to represent the system design activity (Fig. 1.2).

The input of the system design activity consists of information about present and potential products of the system user demand, physical devices that the machine tool builder can select, system architectures (i.e. type of system that can be implemented, such as transfer lines, flexible manufacturing systems) and investment and operating costs. The first output of the FFMS design activity is the assessment of the applicability of focused flexibility to address the production problem; if focused flexibility is applicable, then it is necessary to define the system specifications (i.e. set of resources composing the system) and the timing of system...
acquisition, considering both configuration and reconfigurations. A cost analysis allows also evaluating the economic advantages of focused flexibility.

The FFMS design activity must respect a set of constraints defining the manufacturing strategy, the production requirements and the design goals. Moreover, it is necessary to adopt the data formalization describing product and production system life-cycles. This formalization is presented in Chap. 4 and represents the base on which methodologies and tools to design production systems with focused flexibility can be developed. Methodologies and tools are endowed with a set of mechanisms ranging from reverse kinematics methods to simulation as well as from scenario generation to stochastic programming.

The FFMS design architecture provides a general approach to implement the right degree of flexibility and it allows to study how different aspects and decisions taken in a firm impact on each other. The main characteristic consists in to the development of links among different research fields, such as Manufacturing Strategy, Process Plan, System Design, Capacity Planning and Performance Evaluation. The whole FFMS design approach defined in Fig. 1.2 can be further detailed with the IDEF0 diagram shown in Fig. 1.3. The system design problem is handled by both the system user and the machine tool builder. In particular, the activity “Plan System Capacity” is associated with the system user, while “Design Systems” to the machine tool builder.

Within “Plan System Capacity” activity, the system user identifies the production contexts where focusing the system flexibility can be a good option by developing a strategic analysis (Activity A11 in Fig. 1.4). When alternative
Fig. 1.3 IDEF0 diagram – FFMS Design Activities

Fig. 1.4 IDEF0 diagram – A1 Plan System Capacity
system configurations have been received and analyzed, the system user defines the timing of acquisition of the resources, thus planning the system life-cycle (Activity A12 in Fig. 1.4).

Once the system user has carried out his strategic analysis and defined the system requirements, the machine tool builder starts studying the possible matching among production requirements and selectable resource devices (Activity A21 in Fig. 1.5). The results of this analysis are used to design alternative system configurations in terms of number and type of resources (Activity A22 in Fig. 1.5). Indeed, it is possible to design both systems with focused flexibility and systems whose architecture is characterized by the highest flexibility level, i.e. a Flexible Manufacturing System. This particular configuration will be used to develop a comparative analysis between FFMS and FMS aiming at studying the profitability of the FFMS solution (see Chaps. 7 and 10).

Finally, in order to select the most profitable solution for the analyzed production problem, the alternative system configurations need to be evaluated in term of system performance. This analysis regards the evaluation of the FFMS and FMS performance and is supported by simulation technique (Activity A3 “Compare System Performance”).

1.6 FFMS Design Activities

This section provides a detailed description of the design activities previously introduced, following the information flow represented in Figs. 1.3, 1.4 and 1.5.
1.6.1 Specification of Manufacturing Strategy

The system design process starts from the system user with a strategic analysis which aims at finding out the production contexts where focused flexibility is a winning decision (Bruccoleri et al. 2005). Focused flexibility can be seen as a competitive lever and its specifications should be elaborated within the manufacturing strategy; an approach has been developed to translate strategic decisions into competitive priorities and strategic drivers. This approach has been implemented in an innovative theoretical framework based on the definition of a business strategy and of a manufacturing strategy, together with their impacts on the specifications for the manufacturing system that will be implemented.

Manufacturing strategy is deeply related to the “Test Case Generation” problem. Indeed, to verify the viability of the focused flexibility approach it is necessary to test it in realistic situations which must be devised in coherence with the adopted strategy. A high level strategy defines the position of the firm in the whole market and this decision reduces the domain (and the uncertainties) of possible production problems that the firm is interested in facing. Strategic considerations also lead to the definition of the type and life-cycle of the part family to be addressed. This definition consists of a set of data regarding technological information, part mix and production volumes. A real production context of potential application of the Focused Flexibility concept is typically characterized by:

- products evolving in accordance with their life-cycle;
- product families evolving over time; the product versions can be demanded together or they can be substitutive;
- demand correlation among the product families and among the product versions: positive correlation in the case of complementary products and negative correlation in substitutive products. Moreover, the product (both family and version) life-cycle must respect the growth-maturity- decline shape.

The intrinsic variability of the production problem can lead to different evolutions of demand for each product family and version. An interesting evaluation concerns how the system design process is influenced by the variability of the demand and how to model this type of uncertainty. Since a production problem resulting from the combination of many products can be pretty hard to manage in an evolutionary perspective, the Scenario Tree representation is adopted to simplify the problem representation. Each node of the tree is characterized by a realization probability and it represents a possible production problem in a defined time stage. A wider presentation of this kind of approach can be found in the paper by Ahmed et al. (2003), while a detailed description of the developed approach will be presented in Chap. 5.
1.6.2 Mapping of Requirements on Devices

The collection and formalization of present and forecasted information concerning the production problems represent a key issue for the design problem. In particular, the whole set of data is used by the system user to share information about the part family with his potential system suppliers together with the bid inquiry. After the machine tool builder has collected the necessary information, the technological analysis of the production problem can start. This analysis aims at defining alternative process plans to produce the workpieces and consists of the elaboration of a mapping among the part type and the selectable manufacturing resources (see Chap. 6). This implies to match each feature with an operation or a sequence of operations, taking in considerations the feasible setups. Proper models have been developed and software modules have been implemented to realize a technological link between products and machines by using the information associated with each product (volumes to be manufactured, technological and geometric specifications).

The developed modules take information concerning workpieces, features, machining operations and resources (machines and physical pallets) as input. This information needs to be elaborated in order to find the matching between machines and operations and machines and physical pallets. In particular, setups of the workpieces and the rapid movement times for each setup are evaluated according to the machine performance. A further step consists of configuring the pallet and in turn assigning workpiece setups to pallets in order to develop a set of alternative process plans, i.e. pallet sequences to process the workpieces of the various part families.

1.6.3 Design of System Configurations

Strategic and technological analyses provide the information required to apply configuration methods for focused flexibility manufacturing systems (see Chap. 7). Depending on how the production problem variability, i.e. the evolution scenarios, has been modeled, different configurations methods can developed and implemented: for instance, in the deterministic methods it is assumed to have the perfect information about future whereas in the stochastic models forecasts are assumed to be affected by uncertainty. Moreover, in stochastic models the production problem scheduling during the observed time horizon could determine two- or multi-stage approaches. To clarify the differences just introduced, three different system design models are listed:

- in the deterministic approach (Tolio and Valente 2006) it is supposed that the evolution scenarios are not characterized by a time sequence;
- in the two stage stochastic approach (Tolio and Valente 2007; Tolio and Valente 2008) the temporal sequence of the scenarios and their realization probability are considered;
in the multi-stage stochastic approach the sequence of system configurations and possible reconfigurations are modeled, starting from a more complex scenario tree formulation.

All these methods aim at the minimization of the investment costs and therefore the solutions are optimal from the point of view of the system user but they may not be the best from the point of view of the machine tool builder. Indeed, the machine tool builder aims at maximizing his expected profit and not at minimizing the system cost, even if the two problems are strongly related. A new approach for system configuration considering the point of view of the machine tool builder has been preliminarily investigated by Terkaj and Tolio (2007); the solution provided by such an approach is the offer for the potential client of the machine tool builder, i.e. the system user. This offer consists both of the technological solution (system configuration) and the economic conditions (price, due date).

1.6.4 Planning System Life-Cycle

In the previous sub-section different approaches to design production systems have been described. The machine tool builder obtains as output a set of optimal and sub-optimal system configurations and reconfigurations. However, these solutions need to be evaluated from the system user in order to carry out the planning of the system life-cycle. This step requires an analysis of the technological and economic characteristics of the different available system solutions, in order to carry out an economic and financial appraisal from the system user perspective (Cantamessa and Valentini 2000). A model has been developed for calculating the economic value of the flexibility offered by the different machine tool builders; this model is aimed at supporting decisions on the type and timing of system configurations to be acquired and – coherently with the “focused flexibility” concept – its degree of flexibility. The main concept being used is Real Options Analysis (ROA) (Copeland and Antikarov 2001), which is known to provide a more precise value of flexibility than what classical capital budgeting practices would generate. ROA has already been proposed in literature (Bengtsson 2001; Amico et al. 2007) for evaluating manufacturing flexibility in general, but its application within the context of “focused flexibility” solutions is innovative.

The global structure of the system life-cycle planning approach is composed of two main modules, as it will be deeply illustrated in Chap. 8. The first module takes as input the set of scenario nodes and system configurations and evaluates the performance of each configuration in the different scenario nodes. These values become the input of the second module which provides as output the timing of system configuration over the planning horizon.

These two modules give as output two production system configurations, i.e. a Flexible Manufacturing System and a Focused Flexibility Manufacturing System, both characterized by the minimum system total cost.
1.6.5 Comparison of System Performance

In order to evaluate the real benefits coming from focusing the production system flexibility, the possible system configurations and, above all, the decisions taken by the system user need to be analyzed. The evaluation of the system performance, addressed in Chap. 9, is carried out applying a set of simulation tools (Grieco et al. 2002, 2003).

The innovative aspect relies on the chance to test the different system solutions when facing changeable production problems. In particular, it requires the development of tailored methods and tools for production planning in a focused flexibility system both at loading and scheduling level.

1.7 Introduction to the Structure of the Book

The book framework follows the architecture which has been developed to address the FFMS Design problem. The following chapters will analyze the production system flexibility problem both from the industrial point of view (see Chap. 2) and from the academic point of view (see Chap. 3).

The methodologies to design systems with focused flexibility will be described starting with the formulation of the general data formalization model (see Chap. 4) which enables the communication among all the design modules. Chapters 5, 6, 7, 8 and 9 will present the methodologies and tools related to the five different steps of the design architecture (see Sect. 1.5). All the steps of the architecture are deeply studied, developing methods and tools to address each sub-problem. Particular attention is paid to the methodologies adopted to face the different sub-problems: mathematical programming, stochastic programming, simulation techniques and inverse kinematics have been adopted. Finally, industrial cases and relevant test results will be presented in Chap. 10.

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