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Editor

Design of Flexible Production Systems

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RTL	Rigid Transfer Lines
SFC	Setup Face Configuration
SME	Small and Medium Enterprise
SPD	Standard Placement Direction
STD	State Transition Diagram
SM	Switching Costs Matrix
TAD	Tool Approach Direction
UML	Unified Modeling Language
VRL-KCiP	Virtual Research Lab for a Knowledge Community in Production
WS	Workingstep

Chapter 1
Designing Manufacturing Flexibility in Dynamic Production Contexts

Walter Terkaj, Tullio Tolio and Anna Valente

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

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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 (Terkaj 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

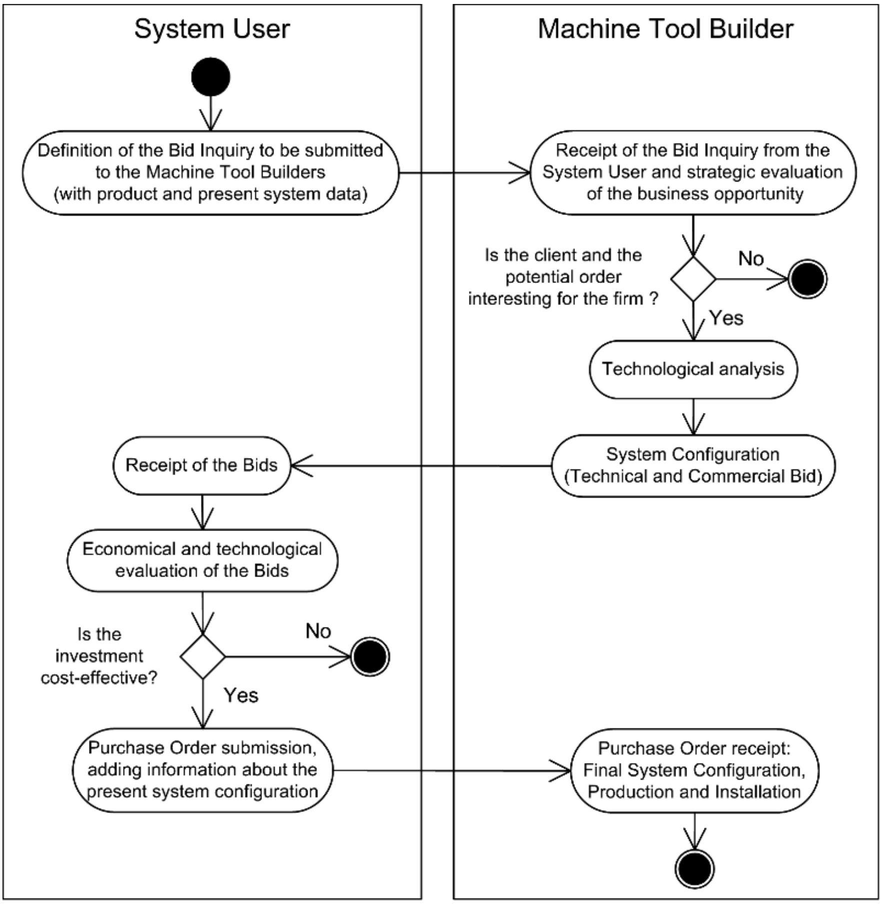

Fig. 1.1 System user and machine tool builder interaction

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

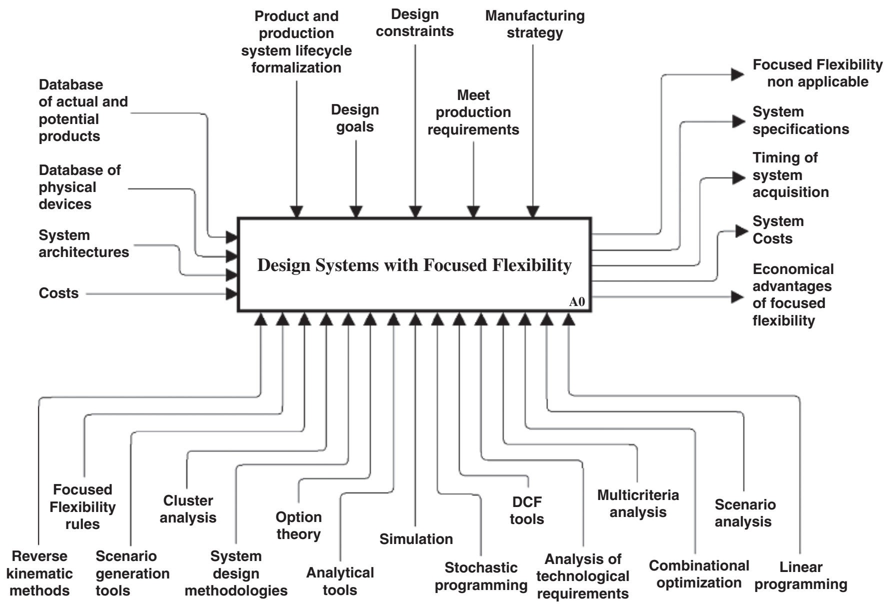

Fig. 1.2 IDEF0 diagram

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

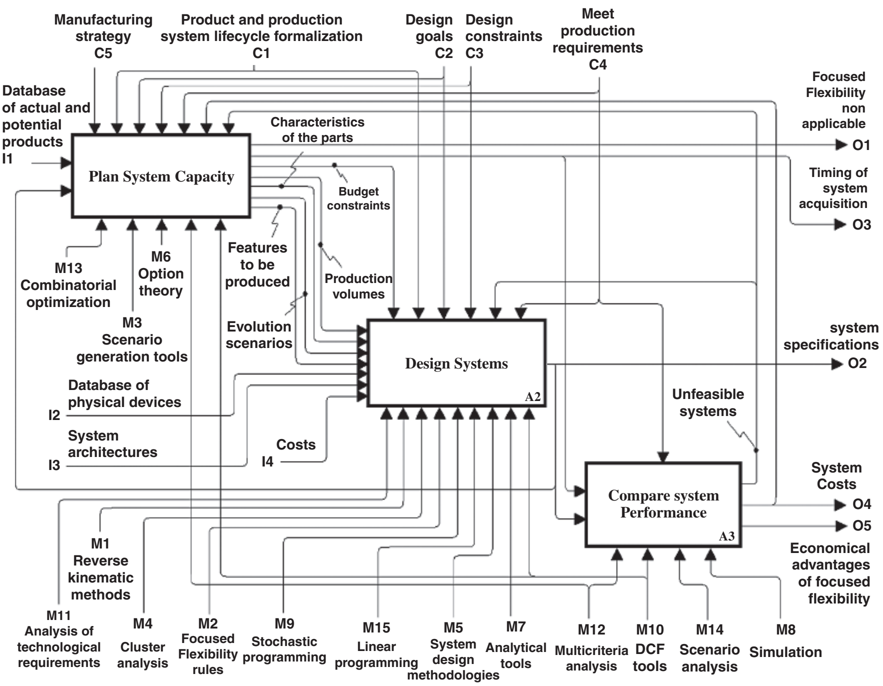

Fig. 1.3 IDEF0 diagram – FFMS Design Activities

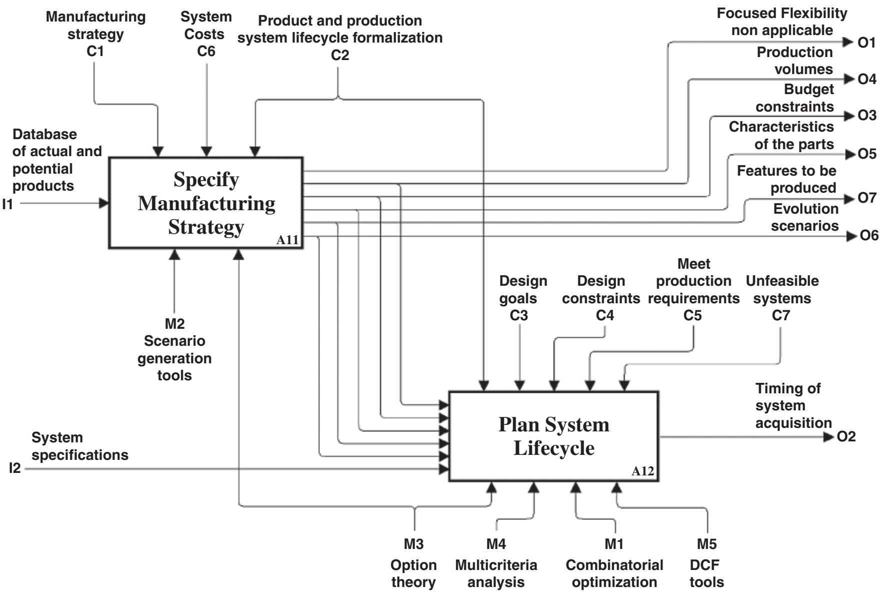

Fig. 1.4 IDEF0 diagram – A1 Plan System Capacity

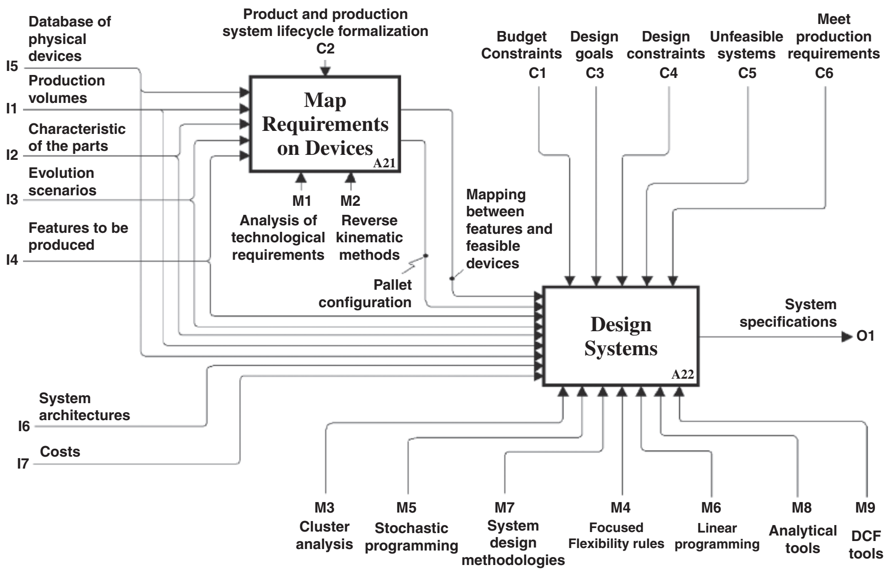

Fig. 1.5 IDEF0 diagram – A2 Design Systems

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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Chapter 2
Flexibility in Manufacturing – An Empirical Case-Study Research

Marco Cantamessa and Carlo Capello

Abstract Since the last two decades, manufacturing firms are facing an increasingly risky environment because of product differentiation, high demand variability and shortening of product life-cycles. Because of these trends, firms need to innovate their manufacturing resources in order to promptly respond to new requests coming from markets. Traditionally, this meant moving from rigid production lines to Flexible Manufacturing Systems (FMS). However, literature and empirical evidence prove that firms have not really located themselves on one of these two opposing manufacturing plant strategies. Rather, they have filled up the vast "gray area" in the middle. Their attempts have been aimed at developing manufacturing system solutions allowing them to precisely supply their markets' needs, and consequently paying for the system flexibility they really need. Because of this, the concept of manufacturing flexibility has to be revised and extended in order to include these solutions involving a "customized" or "focused" architectural flexibility. The current chapter shows the results from the case study research that empirically supports and casts insights in this trend. Based on these findings, a conceptual framework is proposed to interpret how firms perceive the strategic meaning of and realize flexibility.

Keywords Manufacturing flexibility · Empirical research · Real options

2.1 Introduction

As a wide body of literature proves (De Toni and Tonchia 1998), manufacturing flexibility – both at process and product level – has been an important topic in manufacturing since around the Eighties. Manufacturing flexibility allows firms to respond customers' demand by dealing with market uncertainties. Due to

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increasing variability of demand, product variety and shorter product life-cycles, firms need to be flexible enough to produce the components requested by customers with short lead times (Boyer and Leong 1996). These needs have led machine tool builders to develop solutions characterized by a very high operational flexibility, such as Flexible Manufacturing Systems (FMS). However, according to literature, these systems with general purpose machines have not diffused as expected (Handfield and Pagell 1995). Firms are generally quite reluctant to move towards FMSs because they represent decisions of high financial and organizational impact. The initial outlay is so high that it often severely strains firms' financial resources, while the flexibility allowed by FMSs is often oversized with respect to real needs (Tolio and Valente 2006). Moreover, complexity of managing operations in an FMS is also quite high (Matta et al 2000). Empirical evidence confirms that companies need flexibility, because of the requirements coming from markets, but that this can be achieved through different approaches. Viable alternatives are, for instance, combinatorial flexibility deriving from the assembly of standardized components, outsourcing of critical activities, and "focused flexibility" system configurations (Tolio and Valente 2007). The last alternative represents a relatively new concept, which is based on system configurations that aim to meet users' flexibility requirements precisely. Such solutions can be more flexible than conventional "rigid" systems but – at the same time – they do not exhibit all the expensive flexibility of FMSs, which is often left unused (Tolio and Valente 2006).

Chapter 1 of this book defines the FFMS concept and the way with which flexibility is interpreted in this new kind of manufacturing system. This chapter has the objective of providing an empirical foundation to the FFMS concept, and showing the degree with which elements of this paradigm can be actually found in current industrial practice.

The chapter is structured in two main sections. The first section presents the results of the empirical case-study research, whose objective was to understand the way with which flexibility is perceived and managed by both manufacturing system users and machine tool builders. For this purpose, it has been selected a panel of companies to interview, including both system users and machine tool builders. In order to gain a wider perspective, the research was not limited to metalworking, but also investigated other industries. Therefore, in this chapter the term "machine tool builder" will be replaced by the more general term "system producer". Case studies let to capture an interesting set of approaches to flexibility used by the interviewed firms, from both system vendors' and system users' standpoints. The second section covers a proposal for a conceptual model that can be used for reading and understanding the findings of empirical research. The chapter takes the concepts of manufacturing flexibility, focused flexibility and related machine solutions for granted, as a thorough discussion and related literature are already proposed in Chap. 3 of the book.

This chapter is structured as follows: Section 2.2 introduces the empirical research methodology, the interviewed company panel and the results. Next, Sect. 2.3 develops a conceptual framework to read the empirical results and interpret the way companies make flexibility – in terms of both positive and negative feedback. In the end, Sect. 2.4 synthesizes main findings while Appendixes integrate the chapter with some matrixes summarizing information from interviews conducted for empirical research.

2.2 Empirical Research

2.2.1 Methodology

The empirical research has been conducted to reach three main objectives: find out (a) how firms manage and value manufacturing flexibility, (b) which manufacturing system solutions they tend to adopt and (c) how they react to the "focused flexibility" approach. The research has been conducted through "in person" interviews with a set of pre-selected companies. The sample is composed of twelve mid-size Italian firms – that would be the more appropriate target for "Focused Flexibility" adoption – with a consolidated presence on the Italian and international markets (see Appendix 1 for the list of companies. Company names are omitted according to non-disclosure agreements). The main investigated industry is metalworking, however the research spanned other industries where flexible manufacturing machineries are used including textile, wine bottling and woodworking to gain a wider perspective. For each industry, the research included system users and vendors to gain insight into the value chain and have a deeper understanding of the system acquisition process. The intent of the research has been to consider each firm just into the related industry value chain, rather than as a representative of a wider population – i.e. the overall industry.

The research methodology is based on commonly accepted standards for qualitative empirical research (Yin 1994). Interviews and case studies were iterative, interpretative and comparative (Lee 1996) as shown in Fig. 2.1. The iterative approach (i.e. it follows the same process per each industry) is used to investigate how flexibility is managed (i.e. how companies understand their needs, select a degree of flexibility and evaluate investments). The use of a common interview framework allows to collect the same kind of data and to make comparisons easier. The interpretative approach allows to find out and

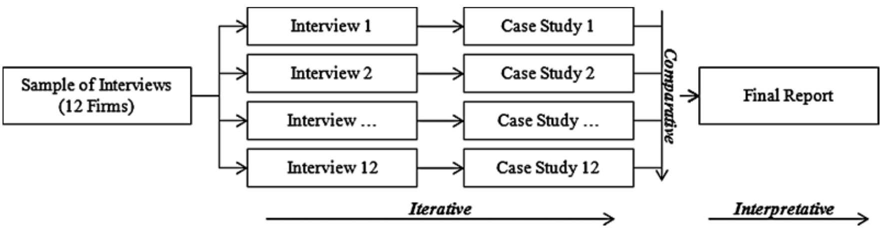

Fig. 2.1 Methodology flow chart

codify elements which were latent in the interviews. Finally, comparisons allow to lead the discussion from an aggregate and more general perspective.

Interviews have been conducted to capture information from different sources by each company: Chief Executive Officers, Manager Directors, Chief Financial Officers, and Production Managers were the main interlocutors for the primary research. Interviews have been semi-structured on three sections. For system producers, three sections have been investigated: (a) the firm's organization, strategy and business context, (b) approaches used to handle clients' flexibility needs and (c) techniques to evaluate flexibility. For system users, the section (b) of the interview framework has been modified to include the required kinds of flexibility and choices for manufacturing systems. Interviews were recorded and transcribed in a case study report. Finally, case studies were integrated in a final document to summarize and compare results (see Appendix 2 for a comparison matrix of main highlights from interviews). The complete research material (details on companies and industries, transcripts of case study interviews, etc.) is available from authors.

2.2.2 Interviewed Companies

The panel of companies interviewed is heterogeneous. It includes companies from 20 up to several hundred employed people. Some companies are privately owned and family-run, others are part of larger international corporations. All of them are profitable and well established on the domestic market while only larger firms serve international markets. Some operate on large markets and are experiencing growth, others serve small niches with stable revenues. All the interviewed companies produce or use some kind of manufacturing systems and look at manufacturing flexibility as a topical and critical matter (see Appendix 3 to know which kind of flexibility each company dealt with).

2.2.3 Results from Empirical Research

2.2.3.1 Business Context

The business context is quite different for the various companies interviewed. Metalworking companies are mainly suppliers for automotive and aerospace industries. Despite obvious differences, they share some common features, such as an increasing product mix, decreasing product life-cycles, the need to expand to foreign markets, and the competition played especially on costs and manufacturing lead-time. In woodworking the empirical research covered plywood production. This industry is quite fragmented, whereas machinery suppliers are few and large. Plywood manufacturers face high uncertainty in matching a highly variable final product demand with scarce raw-material availability. In textile the research covered wool manufacturing, whose process is composed of several phases. Weavers are vertically integrated, while system producers are focused on making machines dedicated to specific manufacturing steps. This industry has suffered over last years because of aggressive competition from Far East producers, downturns in European economies and the introduction of new materials. System producers face a decreasing local demand and try to extend their businesses to new markets, offering their products at prices that barely cover costs without being able to make customers perceive and pay the innovation contents they offer. Winemaking industry has a high degree of vertical integration, going from grape growing to bottling (and sometimes even distributing). The research was focused on bottle filling and labeling. In the case of high-quality producers, the volume and product mix uncertainties does not look very high because of an increasing demand. Moreover, the major source of uncertainty is from the range of bottle types and label materials and dimensions, and not from the type of liquid to be bottled (still or sparkling wine), since producers generally are quite specialized.

2.2.3.2 Manufacturing Systems

Empirical evidence confirmed some expectations about how firms handle investment decisions in new production systems. The interviews revealed that metalworking firms operating in high-volume production tend to exploit existing machinery as much as possible and invest in new resources when it becomes absolutely necessary. Firms operating in niches invest in product-specific machineries in order to achieve the best performance possible. Finally, players operating on a wider and less structured market (typically job shop subcontractors) tend to acquire flexible machines which allow them to cope with a broad, even if not planned, variety of components. However, no companies in the sample implemented fully fledged FMSs: major reasons seemed to be the high acquisition costs and the concern that they were not to able to pay back the investment. The two system producers come from the two ends of the flexibility spectrum: one traditionally builds transfer lines and the other FMSs. However, they are both moving to systems with an "intermediate" degree of flexibility. In the case of the transfer line manufacturer, this is especially due to the need for "manufacturing systems enabling our customers to cover a broader product range and to reduce downtimes when ramping up new products". Their systems are increasingly shifting towards mixed-model lines (i.e. capable to produce different models at the same time), with modular production units that can be easily redeployed at the time of introduction of new products, and with a greater use of CNC machining centers (which – due to the availability of fast linear motors – nowadays allow to achieve production volumes that are comparable to what can be obtained with specialized machinery).

Conversely, the machine tool builder manufacturing FMSs is reducing the degree of flexibility and offering what can be termed "Focused Flexibility Manufacturing Systems" (FFMS). The company stated that "our customers are no longer willing to pay for a flexibility which they know will remain unused. They ask us to tailor new machines on their needs and sell them exactly what they want and nothing more". Focused flexibility generally means a lower flexibility degree on main components of a manufacturing system. Basically, with respect to an FMS, the processing unit has fixed equipments, the tool stock is smaller and less various, and the load-unload process is automatically or robotically managed. Flexible automation is still present in FFMSs, especially in the field of materials handling, but in a smaller quantity. Machines are therefore custom-designed to each customer product portfolio and require some amount of reconfiguration when introducing new products.

In plywood manufacturing uncertainty on raw materials and final products is mainly tackled through component flexibility (in this case, this means that the thin veneers peeled from logs come in many different thicknesses and are then combined in a high variety of panel structures). This requires a highly automated and flexible peeling lathe, while the assembly of panels is mainly left to a traditional process with relatively high labor content. The producer of plywood manufacturing systems stated that "we are able to design and build very flexible lines, but our customers still are quite specialized, and therefore they are not willing to pay for such a high versatility".

Textile producers have to tackle a wide variety of thicknesses, colors, materials and treatments. Weavers could therefore gain from the availability of flexible systems. However, because of technological issues, looms are still highly specialized with respect to materials and yarn thickness. Flexible machines do exist for other process steps, such as washing and finishing. However, due to the difficult market conditions, producers are not gaining benefits when introducing such innovations: "We offer our customers a very flexible machine. However, we are not able to ask them to pay a higher price because of the current market situation. On the other hand, it would now cost us even more to produce a traditional machine with lower flexibility and we are therefore stuck in a difficult situation in which the market expects flexibility, even though it does not value it".

The interviewed winemaking company is a low-volume producer that operates in a niche. Even though it has chosen not to pursue variety with respect to bottles and labels, it has acquired a high-end and flexible bottling line essentially because of its reliability. "Our machine would allow us to fill different types of bottles and to attach paper and plastic labels, but we use only one type of bottle with one label because they represent our brand. However, we bought it because it was the only one allowing us to fill bottles in the safest way. We could even fill bottles with beer and other beverages, but this is not our business. We are willing to pay more even if we do not use such a broad flexibility, because of our primary attention to continuity of service". Producers of bottling lines stated that flexibility is quite important for volume producers that have to cope with many different bottles, labels and fluid content. Such flexibility is achieved through a modular architecture of the bottling line, which in the end does not lead to a substantial increase in costs: "we are always looking for new solutions in order to increase the flexibility of our solutions. Modularity has been an optimal approach allowing us to constantly introduce innovations.

These are the results of several compromises among what our customers wish and what technology allows".

Surprisingly enough, no one of the system users mentioned organizational and cultural aspects as problems connected to managing flexibility in manufacturing. Instead, system producers often did, and especially the machine tool builder manufacturing FMSs. In their view, some of these aspects can be solved by tightening their cooperation with customers, involving both training and a continuing degree of customer support. However, they realize that not everything can be done by them. Customers must complete the process by appropriately integrating flexibility within their manufacturing operations and exploiting its full potential.

2.2.3.3 Flexibility Valuation

Both users and producers perform very rough valuations of manufacturing systems, which generally do not allow to fully perceive and appreciate value coming from flexibility. The smaller metalworking firms (which are generally managed by owners) hardly use any quantitative considerations. Decisions are made through "rules of thumb", and flexibility is generally bought because it is found in high-end machines, which can help to improve the image of their company in the eyes of its customers. Large companies use payback as an investment appraisal method, based on their two-to-three year manufacturing plans. Provided that the investment satisfies the payback limit, they tend to allow manufacturing engineers some freedom in choosing the technology and its flexibility level. In any case, no company examines a mid-to-long term plan and actively assesses flexibility as a competitive lever that may help the introduction of new products. The same goes for the other industries, where managers tend to select manufacturing resources by relying on their own experience and on qualitative considerations. System producers generally make some attempts in quantifying flexibility in technical terms, in order to show their customers the advantages deriving from it. Flexibility indicators are generally restricted to the operational level and do not involve business-level aspects. Among them, the most "strategic" indicator that we found is a "system convertibility" index. This indicates either a "residual value" of the system after the production of a product is phased out, or the "additional investment" that would be required in order to reconfigure the system for producing the subsequent product. It appears that this indicator "encapsulates" many notions that, in academic literature, are treated and discussed as "options".

2.3 Discussion: A Conceptual Model

Once the data gathered from the interviews have been elaborated, a higher-level conceptual model to understand the role of flexibility in the current manufacturing environment is developed. The proposed conceptual model is inspired by

Narasimhan et al. (2004), who tried to understand why flexible technologies do not lead to the desired performance. The authors argued that the results coming from manufacturing flexibility depend on two dimensions: "flexibility competence" and "execution competence". The former represents the ability to correctly invest in advanced manufacturing technologies and to develop systems incorporating flexible resources. The latter represents the ability to convert flexibility capabilities into tangible, operational-level performance. Basically, "flexibility competence" is related to strategic actions and technological capabilities, while "execution competence" is connected to operations management and organizational aspects. According to the authors, flexible manufacturing systems often fail because firms lack either these forms of competence, or because they pursue approaches that are not coherent on these two aspects.

In order to achieve a deeper understanding of these concepts, this chapter adopts an approach similar to the one used by Belassi and Fadlalla (1998), who examined the *process* and the *dimensions* through which competencies in flexible manufacturing are developed.

With regard to flexibility competence, this framework can be integrated with the basic "manufacturing system development process" that has been followed within this book. The process is based on the four steps of (1) strategic planning, (2) system configurations designing, (3) system configurations valuing and (4) purchasing. In this process, system users deal directly with steps 1 and 3, while the system producer handles step 2. According to the empirical findings, this competence can be defined over three main axes: (a) *stratware,* that is the amount of strategic initiatives aimed at major flexibility, (b) *hardware,* that is the amount of manufacturing resources acquired, and (c) *software,* that is the amount of computer-based programs that will support the management of manufacturing operations (Fig. 2.2).

With regard to "execution competence" (Narasimhan et al. 2004), it is worth considering a process that involves producers (who provide training and customer care) and users (who must complete the integration process within the company's operations and deal with day-by-day operational management). Two axis have appeared to be important in this context, and namely (d) *orgware* that is the organizational component, which must be aligned to common

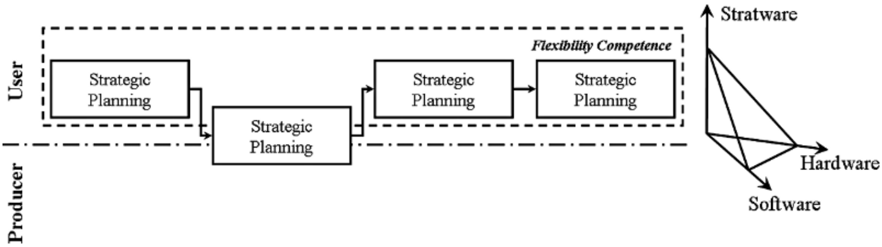

Fig. 2.2 Flexibility competence

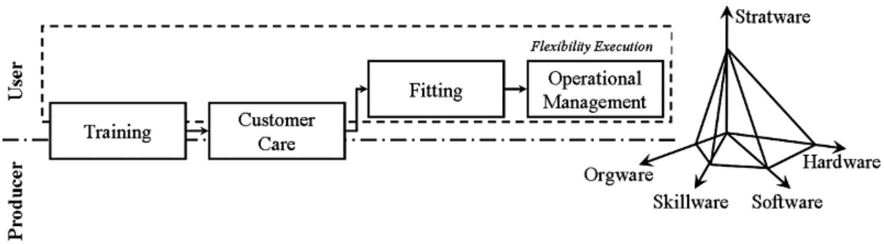

Fig. 2.3 Flexibility execution

objectives and culturally prepared to deal with a change, and (e) *skillware* that refers to fundamental skills for managing new systems (Fig. 2.3).

This conceptual model is based on two competencies which are further exploded in a process and a set of dimensions. It has been mapped against the findings from case studies and seems to capture them fairly well. However, the model is quite complex and difficult to use in order to develop a methodology for supporting decision-making by practitioners. Therefore, it is proposed a synthesis of this model that can be more easily translated to a methodology incorporating algorithmic and/or rule-based decision support. For this purpose, three phases are defined (Fig. 2.4): (a) strategic-level decision making, (b) manufacturing plant configuration, and (c) converting flexibility into results. These phases are sequential and can originate a loop because the strategy needs to be adapted to internal behaviors. In this three phase process it is also easy to locate the role of each player.

When this model is mapped with empirical findings, it becomes evident that it also represents the types of decisions and actions that system users and producers undertake when designing or upgrading their manufacturing systems fairly well. However, empirical evidence shows that these decisions and actions are seldom composed in a well-organized and well-integrated process. This often leads to inconsistencies, misalignment of objectives and suboptimal decisions.

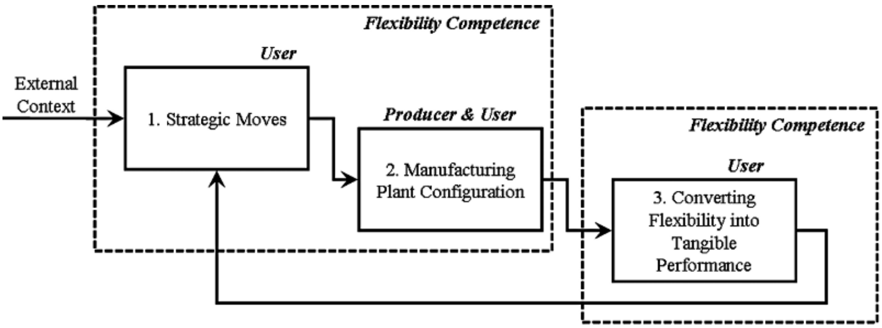

Fig. 2.4 Flow chart of the conceptual framework

In the first phase, interviewed companies often perceive the strategic value of flexibility but are not able to execute it and take all the potential advantages. This can include either giving up investment in flexible machinery (despite the fact that flexible machines are currently becoming cheaper) or not fully using the flexibility that is available in the plant. Therefore, firms often prefer to enact uncertainty- and risk-mitigation strategies. To this purpose, for instance, one metalworking firm focused on serving a small market niche characterized by few customers, highly specific requirements related to precision and quality, small volumes and low product variety. In this way, they gave up the opportunity to exploit a very strong know-how and technology to expand their market. A large company invested heavily in market research to have a better understanding of the future demand scenario. However, they then decided to enter long-term and risk-sharing contracts with car makers that allowed them to reduce the amount of installed capacity and have much of the installed flexibility unused. In other industries, such as textile and winemaking, flexibility is perceived as a way to defend against uncertainty, and rarely as an "option to grow".

In the second phase, choosing the optimal system configuration always comes from the search for an acceptable balance among flexibility needs and the machineries currently in use in the plant, which casts a very strong constraint in the design process. Metalworking companies often have substantial resources available, where older machines are typically dedicated and new ones are more versatile. The common approach is to defer investment as much as possible and to acquire new machines only when it is absolutely necessary. This often happens when the firm acquires an important contract and/or introduces a radically new product.

Looking at flexibility execution, firms were generally in trouble getting flexible systems integrated with their organizational structure. Sometimes the organizational culture was not flexible and open to exploit flexibility. Some issues also are related to fundamental skills, for instance managing complex CNC machines, recovering from anomalies and breakdowns, etc.

In the end, empirical findings confirm that companies do not embrace completely "rigid" or completely "flexible" manufacturing solutions. They rather confusedly tend to buy machines of good quality, which often have embedded flexibility which is then left unused. They do not realize the strategic potential of flexible machinery, and often ask producers to introduce some amount of customization into their machines in order to make them more efficient in manufacturing a specific set of products. Moreover, they tend to see the investment in manufacturing resources as an ongoing process of "manufacturing system evolution" rather than a one-time event. On the other side, system producers are finding that the cost gap between rigid and flexible machines is narrowing and, sometimes, a flexible machine is even cheaper to build than a rigid one. However, they share the difficulty in making customers pay for the value of flexibility, and in integrating machines with existing systems. At the same time, system producers perceive a market opportunity in providing semi-customized systems. Even though the definition of this picture still needs to improve and become clearer, it is possible to state that there is a trend in manufacturing systems towards what can be termed “focused flexibility” (see Chap. 1; Cantamessa et al. 2007). Such trend, or paradigm, is quite unexplored from both an empirical and a normative perspective, and therefore raises the need for methodologies and algorithms dedicated to support the design of “focused flexibility systems”.

2.4 Conclusions

The chapter has tackled a deep understanding of the focused flexibility theory by presenting an empirical research based on case-studies performed on 12 Italian firms (both system producers and users). The aim was to gain a major insight into the flexibility from technological, operational and business perspectives. Research results point out that firms are currently conveying to intermediate solutions that this book is indicating as Focused Flexibility Manufacturing Systems. These solutions allow manufacturing firms to satisfy markets and handle the embedded uncertainty better than they did in the past with rigid or fully flexible solutions. Nowadays technology evolutions and initial scale economies are leading down the price and making these solutions highly competitive. Then, from the demand side, manufacturing firms are increasingly looking at FFMS as the real solutions able satisfy them because tailored right on their needs. Based on these empirical findings, the chapter has proposed a conceptual model to rationalize the “system acquisition process” that connects system producers and system users. This process is often managed with inconsistencies between phases, which cause misalignment between objectives and actions. The framework can be used by actors involved in the process such as the system producer or the system user singularly, or both together. In this way, they could be led to make capacity decisions more consistently with their needs and company future growth perspectives, and moreover they could use the framework as a tool to understand, plan and manage the dealing process with the counter-party. In this way, the concept of focused flexibility could be executed in more correct ways and could lead to better performance results. In addition, the proposed conceptual framework could be adopted by an external analyst for scientific purposes: in fact, it would be helpful to investigate the process in different industries or sub-industries and to understand major dynamics and forces that drive a general system acquisition. Further researches should be dedicated to extend the empirical base to validate this proposed framework, and eventually improve it. At the end, Chap. 2 has highlighted the need to provide a structured methodology to support the system design process in the specific case of “focused flexibility” systems.

Appendix 1 – List of Interviewed Firms

Table 2. 1 List of firms

Firm	Value chain	Industry	Description
Company [1]	System producer	Metalworking	Automatic systems for automotive applications (transfer lines)
Company [2]	System producer	Metalworking	FMS, FMC and FFMS for automotive and aerospace sectors
Company [3]	System producer	Wine	Automatic systems for filling and labeling wine bottles
Company [4]	System producer	Textile	Jenny and mechanisms for different textile processing
Company [5]	System producer	Textile	Machineries for treating weaves
Company [6]	System producer	Woodworking	Systems for shearing and leafing wood panels
Company [7]	System user	Metalworking	Gear and transmission mechanisms for manufacturing machines and automotive industry
Company [8]	System user	Metalworking	Primary and secondary equipments for aerospace industry
Company [9]	System user	Metalworking	Fluid connectors for air conditioner and power steering systems
Company [10]	System user	Wine	Wine producer
Company [11]	System user	Textile	Wool weaving
Company [12]	System user	Woodworking	Wood panel producer

Appendix 2 – Interview Comparing Matrix

Table 2.2 Comparing matrix for system producers (part 1)

Firm	Core business	Industry market	Business context
Company [1]	Design and produce industrial automation manufacturing systems	Automotive (car makers)	Increasing product mix due to product evolutions, new products, decreasing volumes
Company [2]	Design and produce flexible manufacturing cells and systems	Small to medium “third producers”: automotive, aviation, aerospace	Increasing product mix due to: product evolutions, new products, decreasing volumes
Company [3]	Produce filling and labeling integrated systems for wine bottles	Winemaking	High concentration, low product variability, medium environmental elements variability, volume uncertainty managed downstream
Company [4]	Produce jennies and mechanisms for	Textile and mechanic-textile	Increasing industrial dynamic, increasing competition from

Table 2.2 (continued)

Firm	Core business	Industry market	Business context
	different textile processes		far East players, crisis of European market, new input materials, changing demand peculiarities
Company [5]	Produce machineries for treating weaves	Textile and mechanic-textile	Increasing industrial dynamic, increasing competition from Far East players, crisis of European (especially Italian) markets, new input materials, changing demand peculiarities
Company [6]	Design and produce manufacturing lines and machineries to shear and leaf wood panels	Woodworking	Small and specialized industry, high concentration (one player operates on the international scenario), high customer's bargaining power

Table 2.3 Comparing matrix for system producers (part 2)

Firm	Uncertainty sources	Flexibility concept
Company [1]	Product types, product mix and product volumes	More product models on manufacturing line, possibility to reconvert manufacturing system, manufacturing capability scalability
Company [2]	Product types, product mix, product volumes	Under acceptable time-cost constraints, a flexible system is to be able to process a set of inputs, perform different manufacturing programs, generate a set of outputs
Company [3]	Filling: Content (flat or sparkling wine), Bottle characteristics (height, width, shape)	Flexible system is to: be able to handle different uncertainty forms, be easy to use and maintain, have an acceptable technological availability-costs trade-off
	Labeling: Bottle shape, Label positioning on the bottle	
	Label characteristics: Shape, Type (transparent or not)	
Company [4]	Physical properties: Raw material, Fiber dimension characteristics, Input-output color, Jenny type, Spun yarn type based on Code, Wrench degree, Persistency and Regularity	Flexible system is to be adapted to different raw material physical properties
Company [5]	Physical and chemical properties: Yarn wrench degree, Fiber properties, Yarn origin	Flexible system is a modular system able to perform the 5 typical treating weaves activities according to the available technology

Table 2.3 (continued)

Firm	Uncertainty sources	Flexibility concept
	Manufacturing type: Treatment, Required quality level	
Company [6]	Leafed: final scruff dimension, thickness, essence to be processed (standard or exotic) Sheared: thickness, final dimensions, essence to be processed (standard or exotic)	Machinery or manufacturing line bale to process different materials

Table 2.4 Comparing matrix for system producers (part 3)

Firm	Flexibility solution(s)	Technology specifics
Company [1]	Modular manufacturing systems with: single-chuck unit for mechanic finishing, multi-chuck unit for standard components	Use of sequence of linear engines, high automation elements, robotics
Company [2]	FMC, FMS, FFMS	Cutting-edge sophistication on 3 main elements (process unit, tool stock, piece and equipment unit), use of automation and robotics for stand-alone systems
Company [3]	Modular systems. each module can be provided with a certain flexibility degree according to: technology availability, economic convenience, customer requirements	Use of universal tools as well as versatile, parallel rigid units and check points
Company [4]	Jenny: able to process different raw materials with different physical properties, dedicated to fiber type, able to process a certain set of product codes	Use of electronics to improve automation, modular loglines to convey different raw materials to the same jenny
Company [5]	Modular machinery, each module is dedicated to a specific manufacturing activity, high versatility	Check systems to maximize work flow, maximize work quantity, minimize scruffs for no conformity to output specifics and reduce human error
Company [6]	Standard essences: machineries-manufacturing lines able to process input materials according to pre-set dimension ranges Exotic essences: machineries-manufacturing lines able to handle all uncertainty elements and match customer requirements	Use of electronics, particular materials handling, embossed chucks and laser devices

Table 2.5 Comparing matrix for system producers (part 4)

Firm	"Needs-solutions" matching	Operation flexibility value	Operation flexibility performance indicator
Company [1]	Yes	Improved production performance index	Product variety to be processed randomly or with setup, product mix tiding up frequency, average WIP time
Company [2]	Too much flexibility for FMSs	Improved performance indicators, human operator separated by machinery	They do not measure operation flexibility for their products
	Yes in the case of FFMS		
Company [3]	Yes	Decreased set up time, decreased product mix variety, adaptability to vessel shape, major label variety	Qualitative standpoint: bottle variety, filling variety Quantitative standpoint: number of bottles that can be filled by time unit
Company [4]	No	Decreased set up time, improved production performance index performance	They do not measure operation flexibility for their products
Company [5]	Too much flexibility (they cannot sell it, customers does not understand the real value)	Versatility in terms of: materials (weave type), manufacturing types	Versatility in terms of qualitative (manufacturing variety, weaving variety) and quantitative (weave per hour meters) indicators
Company [6]	Yes	Decreased need of human resources in production line, improved production performance	Versatility is measured only from the qualitative standpoint: type of manufacturing process and type of processed material

Table 2.6 Comparing matrix for system producers (part 5)

Firm	Flexibility economic value	Flexibility economic value indicator(s)	Capital budgeting practices	Customer investment decision making[a]
Company [1]	Recovery value	Productivity, investment usability, average system life that increases due to system	Net present value, scenario analysis, payback period	Strategic choices to introduce new products and increase manufacturing capability

Table 2.6 (continued)

Firm	Flexibility economic value	Flexibility economic value indicator(s)	Capital budgeting practices	Customer investment decision making[a]
		recoverability, investment scalability		
Company [2]	Saved working hours	Not available	Net present value	Strategic and tactical choices to renew rolling stock and increase plant and system flexibility
Company [3]	Set up cost decreasing, brand and marketing payback, manufacturing quality	They do not have indicators	Rough valuations, qualitative considera tions	Strategic choices to renew rolling stock, increase manufac turing capability and maximize production cycle automation
Company [4]	Set up cost decreasing	They do not have indicators	Payback period	Strategic choices to renew rolling stock, increase manufacturing capability and expand businesses to new market
Company [5]	They do not see an economic value for flexibility	They do not have indicators	Cash flow analysis	Strategic choices to renew rolling stock, increase manufacturing capability, diversify product mix and maximize production cycle automation
Company [6]	Customers perceived the flexibility value as high	They do not have indicators	Entrepreneurial capabilities, cash flow analysis	Operation choices to perform different types of manufacturing activities and process no standard raw material

[a] It refers to elements that lead potential customers to ask to system producers for a manufacturing system investment assessment.

Table 2.7 Comparing matrix for system users (part 1)

Firm	Core business	Industry market	Business context
Company [7]	Produce gear and transmission mechanisms for manufacturing machines and automotive industry	Market niches small automotive players, aviation industry, International	Few competitors in the domestic context, few customers, production volumes are never more than 50 units
Company [8]	Produce primary and secondary equipments for implementation systems, startup systems and fuel check systems	Aerospace (manufacturers), International	Information flows were totally upset after "09/11" events, high customer bargaining power, long term planning horizons
Company [9]	Produce assembled tubes for air conditioning and power steering	Automotive (car maker), International	Low concentration degree, small size competitors, price taker, high customer bargaining power
Company [10]	Produce DOC and DOCG wines (especially Barolo variety)	High-quality consumers, International	High environment uncertainty, few competitors
Company [11]	Produce and treat spun yarns and weaves with natural fibers	Female tailor's shops, International	Huge field, a lot of competitors, especially from Far East countries, crisis of Italian market, changing market demand, decreasing lead times
Company [12]	Produce multilayer poplar wood panels	Home furniture, caravan furniture, wood handcrafted manufacturing	Small field, low concentration, fragmented, a lot of competitors, few European competitors, no international competitors

Table 2.8 Comparing matrix for system users (part 2)

Firm	Uncertainty sources	Flexibility concept	Adopted solutions for flexibility
Company [7]	Product mix: input dimensions, output characteristics	Something nice to have, thought as free machine versatility, it is not perceived as necessary	Machineries are rigid, they are considering to acquire some function integrators, they realize flexibility at the plant level, outsourcing several activities

Table 2.8 (continued)

Firm	Uncertainty sources	Flexibility concept	Adopted solutions for flexibility
	Changing volumes based on job order, customer requirements and lead time		
Company [8]	Product mix: piece types, low volumes, output quality	Ability to process different pieces on the same machinery	They select major added value components, new machineries tend to be more flexible, old machineries are utilized as exceeding manufacturing capacity, techniques to optimize production
Company [9]	Product type based on model news Model version by evolution, geography, input characteristics, manufacturing activity to accomplish Large and highly variable volumes, small life-cycle products	System ability to execute the main manufacturing activity on more inputs in terms of different materials and geometries	General purpose machineries, reducing upstream uncertainty by negotiating rules and risk assumptions with contractors, studying the potential success of each car model before taking the job order
Company [10]	Flat wine variety, need to satisfy customer needs, environment events that affect raw materials, and therefore final products	It is not perceived as necessary, filling process must be executed safely and without stops	Oversize filling and labeling machineries
Company [11]	Spun yard type by codes, colors; manufacturing types, treating practices variety	Lean manufacturing processes to respect manufacturing times and customer requests	Internal orders handling by component stock, standardized manufacturing process to create components, use of outsourcers for extraordinary orders
Company [12]	Raw material: dimensions, structures; end product: manufacturing type, manufacturing variety, dimensions	Machinery adaptability to process variables, i.e. dimensions and structures	Company strategy to optimize production cycle, standard products supplied to market, use of components from outside suppliers

Table 2.9 Comparing matrix for system users (part 3)

Firm	Technology specific(s)	"Needs-solutions" matching	Operation flexibility value
Company [7]	Rigid machineries oriented to execute precision manufacturing activities	Yes	Increased product mix that can be processed by a machinery
Company [8]	Machineries characterized by: high automation degree	Yes (thank to optimizing production procedures)	Increased manufacturing capacity
	High tool number		Increased variety
	Acceptable (time and cost)set ups		Human resources separated by the manufacturing machinery
Company [9]	Machineries characterized by high automation degree, numerical control, flexibility in the quality control as well	Yes (thank to car makers' long term plans)	Manufacturing phases integrated on the same machinery, increased product mix, no other than check role assigned to human resources
Company [10]	These are the same elements as for company [3], given that they are their only supplier	Yes (thank to oversize machineries)	No measure
Company [11]	Use versatile machineries See company [5], they are their main supplier	Yes (thank to continuous changes to production process)	Potential use of standard components, dispatched orders by set time
Company [12]	Use of a versatile machinery at the start of the manufacturing line, exactly where there is the need of flexibility. In this way, outputs can be standardized to reduce uncertainty along the downstream phases Versatility used as a way to reduce the need of human operators handling machineries	Yes	Reduced set up time, used components, reduced production process complexity

Table 2.10 Comparing matrix for system users (part 4)

Firm	Operation flexibility performance indicator	Flexibility economic value	Flexibility economic value indicator
Company [7]	Qualitative indicators	New machinery investment saving	Qualitative indicators
Company [8]	Number of performable pieces, manufacturing time cycle	Set up costs saving compared with old machineries	Qualitative indicators and production indicators
Company [9]	Number of performable manufacturing activities, number of performable inputs in terms of materials and geometries	Cost reduction (given that they are price takers, cost reduction allows them to reach a higher gross margin)	Qualitative indicators and production indicators
Company [10]	Number of bottles that can be filled by time unit	Positive feedback from the market (to be translated to economic value), customer willingness to pay a few more	No measure
Company [11]	Versatility from the qualitative standpoint in terms of type of manufacturing activities accomplished, manufacturing activity variety	High value perceived by the company, alas this value is not recognized by the customers	Qualitative level
Company [12]	Number of manufacturing activities, type of manufacturing activity, dimension range of processed material	Manufacturing cost reduction, additional costs are turned to customers	Positive feedback for the market

Table 2.11 Comparing matrix for system users (part 5)

Firm	Capital budgeting techniques	Investment decision making
Company [7]	Rough evaluations, use of entrepreneurial experience and mind	Driven by product, customer requirement, based on technical performance
Company [8]	Cash flow analysis, payback period	Based on technical performance, consistency with production program, driven by new job orders
Company [9]	Cash flow analysis, use of entrepreneurial experience, recovery value	Based on new job orders, time constraints, driven by customer needs
Company [10]	Rough estimations, qualitative considerations	Machinery reliability

Table 2.11 (continued)

Firm	Capital budgeting techniques	Investment decision making
Company [11]	Cash flow analysis, evaluations based on experience	Machinery reliability, possibility to expand to new markets
Company [12]	Use of experience	Based on internal needs such as to increase capacity

Appendix 3 – Company Panel Analysis by Flexibility Dimension

Table 2.12 Flexibility dimensions by company

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
Machine flexibility	×	√	×	×	×	√	√	√	√	√	√	√
Labor flexibility	×	×	×	×	×	×	√	√	√	×	×	×
Material handling flexibility	×	√	×	×	×	×	×	×	×	×	√	×
Routing flexibility	×	√	×	×	×	×	×	×	×	×	×	×
Operation flexibility	×	×	√	×	√	×	√	√	√	×	×	×
Expansion flexibility	√	√	×	×	√	√	×	√	√	√	√	√
Volume flexibility	√	√	√	×	√	√	√	√	√	√	√	√
Mix flexibility	√	√	√	√	√	×	√	√	√	×	√	×
New product flexibility	√	√	√	×	√	×	×	√	√	×	√	×
Modification flexibility	√	√	√	√	√	×	√	√	√	×	√	×

Source – Koste and Malhotra (1999)

Interviewed companies were investigated to have a major understanding of, among all, what kind of flexibility they were utilizing internally or selling to their customers. Following some studies from literature (Koste and Malhotra 1999, Vokurka et al. 2000, Shewchuk and Moodie 2004), companies were analyzed based on ten classical flexibility definitions. Results shows that each company implements internally or sells at least three flexibility forms. Table 2.12 shows all the flexibility forms by company. The next chapter will consider several potential taxonomies and framework according to the multi-dimensional nature of flexibility and many contributions from reference literature. Then, it will introduce a flexibility ontology, defining a set of four basic flexibility dimensions – capacity, functionality, process and production planning -, listing four attributes – range, mobility, uniformity and resolution – and three basic levels – flexibility, reconfigurability, changeability.

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Chapter 3
A Review on Manufacturing Flexibility

Walter Terkaj, Tullio Tolio and Anna Valente

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 when designing a manufacturing system and its flexibility; indeed, 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 proposing also a conceptual framework for its formalization.

Keywords Focused flexibility manufacturing systems (FFMSs) · Flexibility review · Ontology on flexibility

3.1 Current Literature on Manufacturing Flexibility Topic

The 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, Chap. 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 implementation of focused flexibility.

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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 and although they 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 aiming at systemizing the high number of flexibility definitions since they could be helpful within the system design phase.

The next sub-sections will present the works that can be grouped the four literature categories.

3.1.1 Manufacturing Flexibility Analysis

The analysis of manufacturing flexibility has been 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 (Slack 1983; Gerwin 1987; Kumar 1987; Sethi and Sethi 1990; Chen and Tirupati 2002). 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 Fig. 3.1.

These works highlighted the need for investigating the relationship between the production requirements and the manufacturing flexibility forms (Upton 1994; De Toni and Tonchia 1998). In particular, a key issue is to identify the

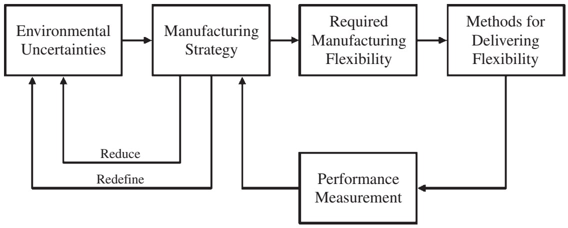

Fig. 3.1 Approach developed by Gerwin (1993)

flexibility forms that 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.

Hyun 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) 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 proposed 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 and 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 to cope with environmental uncertainty and also to 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 and Production, Market and Expansion and 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 that 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, 2003).

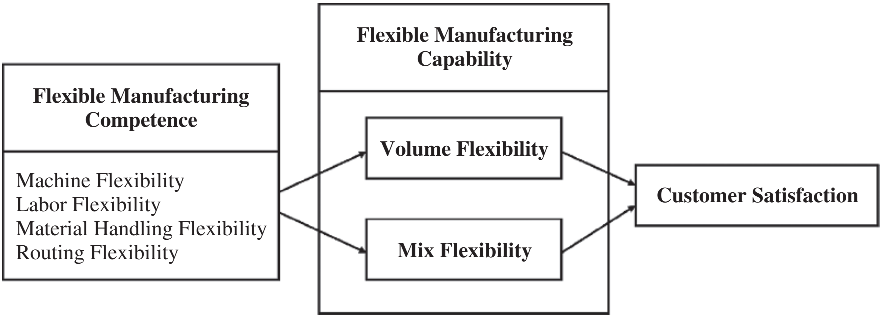

Fig. 3.2 Framework proposed by Zhang et al. (2003)

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 (Fig. 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.

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 authors 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. 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 with purchasing high level of flexibility, taking into account the relevant investments (Stecke 1985; Matta et al. 2008).

Other works have studied the relationship 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 the purchase of 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. Indeed, 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 economic evaluation is accomplished to support the importance of flexibility and adaptability for manufacturing systems. The decision about when to buy flexibility is related to the risk analysis of investments (Kahyaoglu and Kayaligil 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.

Since 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 (Brandimarte and Mottola 2007).

Economic 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 changes that were not forecasted.

ElMaraghy (2005) linked the concept of manufacturing system life-cycle to manufacturing system 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 (Ganzi and Tolio 2003; Tolio and Valente 2006, 2007, 2008). The methods presented in these papers will be analyzed in Chap. 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 aiming at describing 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* (Fig. 3.3). Each *Basic Flexibility Form* is defined as the aggregation of two key concepts: *Dimensions* and *Levels*.

Basic Flexibility Dimensions are general and 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.

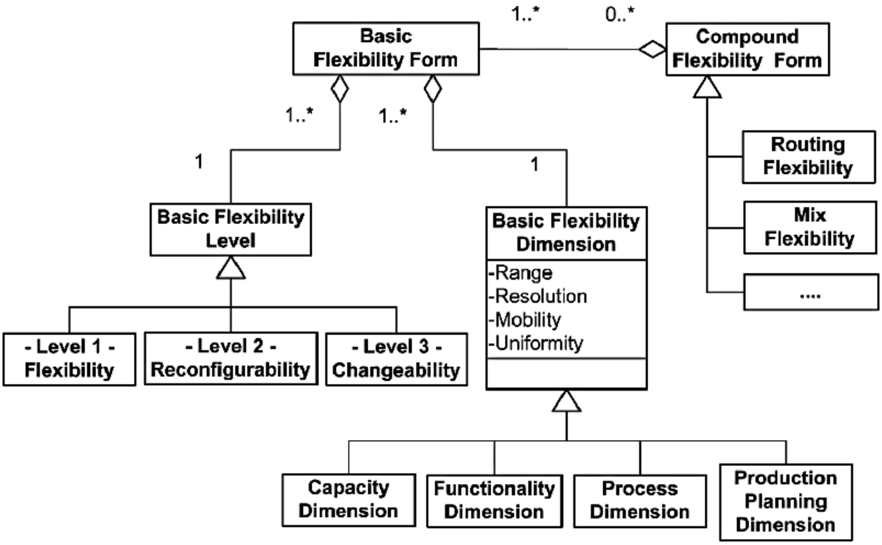

Fig. 3.3 Ontology on flexibility (Terkaj et al. 2008)

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.

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

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

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. Indeed, 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.

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.

The proposed ontology on flexibility is tested in this chapter carrying out two types of analysis. Firstly, the possibility to map all the forms of flexibility described in the existing literature through the *basic dimensions* and *levels* is investigated in

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

Sect. 3.2. Secondly, the attention is focused on the forms of flexibility in industrial production contexts in 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 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.

Table 3.4 Flexibility forms 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 et al. (1999)	Expansion	Level 2, Level 3	Level 2, Level 3	–	–
Parker and Wirth (1999)	Expansion	Level 2, Level 3	–	–	–

Table 3.4 (continued)

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 and 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 et al. (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 (2005)	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	–	–

Table 3.4 (continued)

Paper	Compound flexibility form	Cap	Func	Proc	Plan
Kara et al. (2002)	Material-handling	–	Level 1	–	–
Zhang et al. (2003)	Material-handling	–	Level 1	–	–
ElMaraghy (2005)	Material-handling	–	Level 1	–	–
Grubbstrom and Olhanger (1997)	Product Mix	–	Level 1, Level 2	–	–
Ramasesh and Jayakumar (1997)	Product Mix	–	Level 1	–	–
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 (2005)	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

Table 3.4 (continued)

Paper	Compound flexibility form	Cap	Func	Proc	Plan
Parker and Wirth (1999)	Routing	–	–	–	Level 1
Kara et al. (2002)	Routing	–	–	–	Level 1
Zhang et al. (2003)	Routing	–	–	–	Level 1
ElMaraghy (2005)	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 (2005)	Process	–	Level 1	–	–
Gupta and Somers (1996)	Product and production	–	Level 1	–	Level 1
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 (2005)	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	–	–

Table 3.4 (continued)

Paper	Compound flexibility form	Cap	Func	Proc	Plan
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 (2005)	Volume	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 that are rather difficult to compare without using the dimensions and the levels.

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*. 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 Co., Ltd., one of the biggest Japanese machine tool builders, proposes to its customers a range of solutions to face the increasing need 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. Indeed, 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 operations 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 (Fig. 3.4) are machining centers designed for mass production applications.

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 a 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

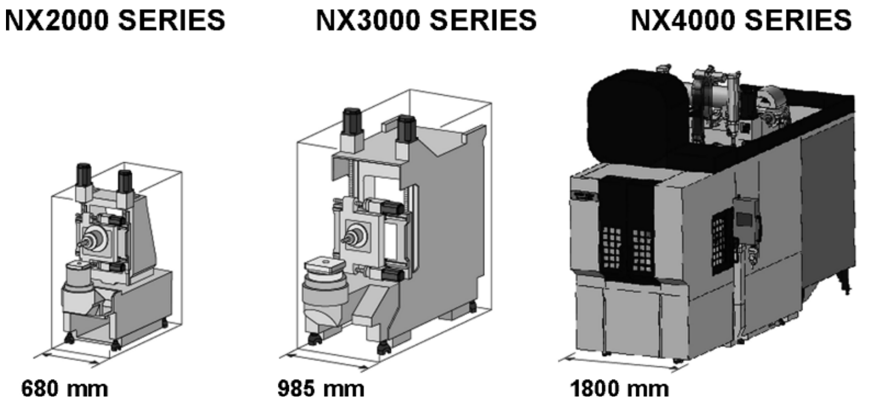

Fig. 3.4 Mori Seiki machines of the NX series (courtesy of Mori Seiki)

higher precision in the operations. 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, the table and the machine body. This means a reduction in the number of setups together with shorter 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 that 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 Figs. 3.5 and 3.6.

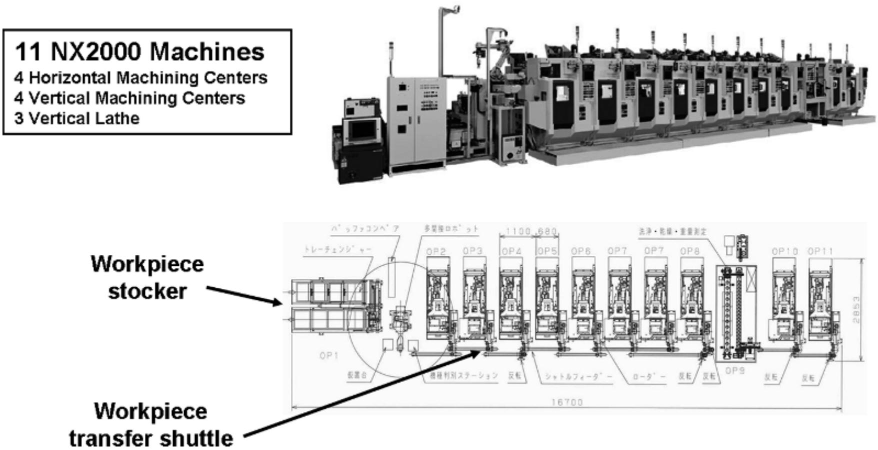

Fig. 3.5 Impact of small machines at a system level – travel distance is reduced by 30% compared to previous models (Courtesy of Mori Seiki)

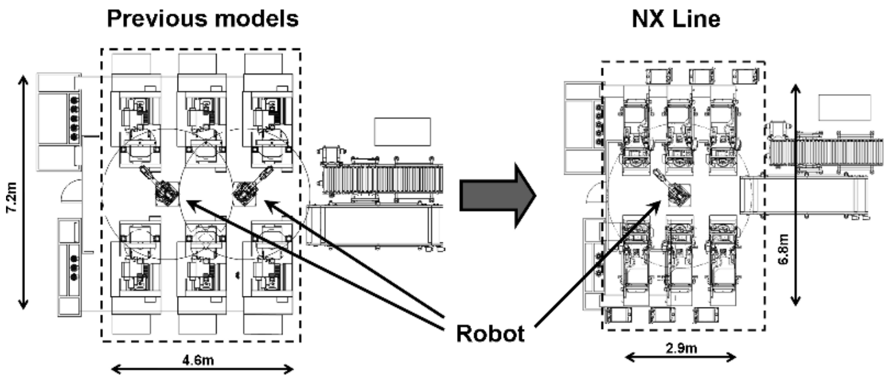

Fig. 3.6 Impact of small machines at a system level – floor space is reduced (courtesy of Mori Seiki)

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 manufacturing systems are provided with Capacity, Functionality, Process and Production Planning Flexibility. Capacity flexibility is given by the modularity of the machines. Indeed, being modular and highly interoperable, machines can be added or removed from a production line according to the current demand (Fig. 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.

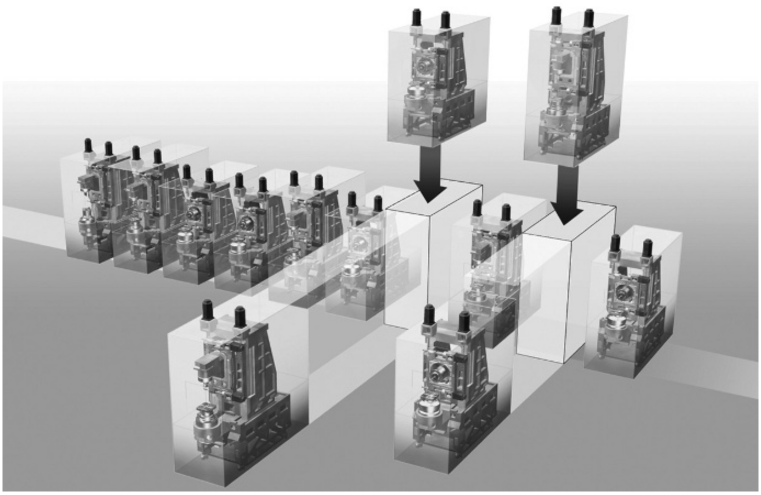

Fig. 3.7 Capacity flexibility through modularity (courtesy of Mori Seiki)

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

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.

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.

The manufacturing systems offered by Mori Seiki are a clear example of systems with focused flexibility. The flexibility has been focused mainly thanks to the adoption of machining centers with a small work cube. Moreover, it is not required to adopt only general purpose machining centers; indeed, 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 an extensive literature review and by adopting an innovative ontology on flexibility. Resulting evaluations emphasize the first findings of the empirical research developed in Chap. 2. Firstly, the production problems analysis, even in an evolutionary perspective, represents a very critical task for the 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 confuse the decision maker 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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Chapter 4
Product-Process-System Information Formalization

Marcello Colledani, Walter Terkaj and Tullio Tolio

Abstract This chapter introduces a conceptual framework for the integrated modeling of product, process and production system data. The work focuses on the Manufacturing System Design problem and aims at providing a common data structure as a reference for different methodologies and tools in this domain. The framework is flexible, extendible, scalable and has been developed as an object-oriented model by means of UML (Unified Modeling Language). Moreover, the proposed data model can have a wider applicability since it is based on shared standards and previous general frameworks. The concept of evolution has been introduced into the model, since it is essential to include market uncertainty in the design of competitive production systems. Finally, the developed framework has been translated into a relational database which can be interfaced with all the main phases of the system design approach presented in this book.

Keywords Manufacturing information formalization · Production system data · Product data · Manufacturing process data · STEP-NC

4.1 Introduction

Chapter 1 has already introduced the problem of manufacturing system design, highlighting the wideness and complexity of the activities that it is necessary to carry out in order to obtain effective system solutions (see Sect. 1.1). Above all, the turbulence of the market environment makes hard to tackle the configuration, reconfiguration, implementation, management, control and continuous improvement of the production systems which have to cope with the changes of products and processes.

This chapter aims at establishing a common view and defining a common structure to handle the information used and generated during the design of manufacturing systems. From the industrial standpoint, this problem is highly

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critical since on one side many economic and technological issues must be jointly considered and on the other the final result has a strong impact on the profitability of the firm. System design can be time consuming and expensive, since qualitative and quantitative aspects are analyzed. Therefore there is the need of support tools to make the procedure of system configuration more efficient, so reducing the process time, and more effective, so increasing the chance to design the best configuration (Cantamessa et al. 2007). Chapter 1 has introduced system design as a complex problem which requires to share data among different activities (Fig. 1.3) including manufacturing strategy, process planning, system configuration, capacity planning and performance evaluation. A holistic and integrated view is necessary to model the most important relations among the different aspects of the manufacturing environment and it is also necessary to develop a unique standard framework to formalize data on products, processes and production systems. All the data necessary for system design activities have been formalized by following an innovative integrated data structure for evolving product-process-system. This integration is fundamental to optimally address the design problem, because most of the data are strongly related. The data framework has been enriched with the evolutionary concept which has been introduced to consider possible changes of the system (i.e. reconfigurations) as well as of the products/processes. Given the uncertain environment that manufacturing firms have to cope with, it is necessary to consider the evolutionary dynamic when designing a production system. Indeed, the system life-cycle is longer than the product life-cycle and, since the best system configuration is time-varying according to the product evolution, some system reconfigurations could be required to optimally address the production problems.

The data formalization introduced in this chapter has been adopted as a reference by all the methodologies and tools that are described in the chapters of this book. The following section briefly analyzes the literature, Sect. 4.3 profiles a detailed object-oriented data formalization, while Sect. 4.4 presents its implementation in a relational database.

4.2 Literature Analysis

The problem of data formalization has received much attention in literature: knowledge-based analysis methodologies and tools have been developed to support the decision making processes all over the product/process/system life-cycles. Bernard and Tichkiewitch (2008) made a contribution to this area, proposing a book with a complete overview of the knowledge life-cycle management topic with the most recent and innovative results. However, data evolution is not fully addressed by academic models and is not faced at all by industrial standards. Moreover, the integration among product, process and production system data have not yet been solved.

A framework to manage manufacturing information should be able to support the user in the production modeling activity and feed the decision support tools with the required data. Casati and Pernici (2001) have outlined four main requirements for a knowledge management framework:

- *Flexibility*: the model must be easily adaptable in order to describe many different production system architectures, processes and product features.
- *Extendibility*: the model must guarantee the potential for the user to rapidly extend the range and/or detail level, if needed.
- *Scalability*: the model must be able to support product, process and production system descriptions at different levels of detail.
- *Integration*: products, production processes and systems, together with their relations, must be considered and described in the same framework, since they all belong to the manufacturing environment.

The problem of developing a data formalization framework for a manufacturing context has been traditionally faced by proposing solutions which can be in some cases easily adapted to different situations but which do not take into account all the requirements defined above. The main drawback is that existing models generally consider products, processes and production systems as separated from each other, and integration is not fully addressed. Moreover, the evolutionary aspect has been hardly faced, even if it has a deep impact on the performance of a manufacturing system (see Sect. 1.4).

The following sub-sections briefly analyze the literature about product, process, production system and their integration.

4.2.1 Product and Process

Product life-cycle issues have been examined in recent years from many different viewpoints. The available models range from marketing models, dealing with curves describing the evolution of product demands, to models dealing with the evaluation of the environmental impact on the product life-cycle (LCA – Life-Cycle Analysis), to management models dealing with the costs related to the various phases of the life-cycle, to more technical approaches considering product-process engineering activities along the life-cycle. What is still missing is a complete view from the perspective of the machine tool builders. This view should integrate the various viewpoints providing information to support the design of the production system life-cycle connected with the product life-cycle. The completeness attributed to this viewpoint is strictly connected to the need to describe the product evolution over time in terms of number and type of product variants, sales volumes and technological characteristics such as the raw piece description (e.g. shape and material) and the required machining operations (i.e. process plan).

The uncertainty affecting the product evolution, nowadays more critical than ever, should also be modeled in the most appropriate way. Important product information models are provided by industrial standards such as STEP (ISO 10303) and PLCS (ISO 10303–239). Anyway, these standards do not allow to describe both the geometric information about a certain product variant, and the information concerning the process cycle. This results in a static description of a product type, not considering the uncertain evolution over time of the different product variants.

PSL (Process Specification Language) project (ISO/CD18629 2002) is an interesting approach in the field of process knowledge formalization. PSL provides a language for process data exchange to integrate multiple applications handling data related to processes throughout the manufacturing context life-cycle.

Paying attention to the integration between product and process, the STEP-NC standard (ISO 14649) presents a model of data interoperability between CAD/CAM systems and CNC machine tools. This standard has been taken as a reference to develop the product and process side of the data formalization presented in this chapter.

4.2.2 Production System

From the production system standpoint, many works have been developed in the past to define languages and methodologies for its description, analysis and design. All these tools are useful but can be used only to describe the static and dynamic behavior of a single version of the production system. However, in everyday practice a system can undergo many kinds of evolution, driven mainly by product and process modifications. To model such changing systems, tools for the description of different evolution scenarios, with the related information concerning probabilities and durations, should be defined and used.

Many works adopted an object-oriented approach to model manufacturing systems. In these works, the manufacturing system is decomposed into objects instantiated from classes. Each object has an identity, a state and a behavior following the object-oriented paradigm. Van Brussel et al. (1995, 1998) presented a holonic reference architecture for manufacturing systems modeled with UML class diagrams. Park et al. (1997) proposed an object-oriented modeling framework called JR-net for a generic AMS (Automated Manufacturing System); resource-type, job-type and control-type objects compose the model of a generic AMS. Kellert et al. (1997) proposed a conceptual model for FMSs (Flexible Manufacturing Systems). Booch et al. (2004) proposed another object-oriented model for FMSs. The authors adopted the OMT (Object Modeling Technique) formalism to model the static portion of the system, DFD (Data Flow Diagram) for the dynamic and functional models, and STD (State Transition Diagram) for the control aspects.

Bruccoleri et al. (2003) and Matta et al. (2004) proposed UML-based modeling approaches to describe all static and dynamic aspects of a cell controller and a complete FMS, respectively.

4.2.3 The Integration

The need for integration of the two previous aspects (the product/process and the production system) directly derives from the viewpoint of the machine tool builder who wants the vision on the design and management of his product lifecycle (i.e. the production system seen as a product according to the vision proposed by the Manufuture Platform) to be as complete as possible. Moreover, the machine tool builder aims at deriving a guidance to handle the most critical issues occurring within the system design problem. For example, starting from the description of how the product will probably evolve over time, it is possible to take very critical decisions, e.g. whether to acquire some kind of flexibility at a certain degree, focused on some aspects relevant to his production problem, or to opt for more rigid and productivity-oriented system solutions.

Regarding the integration of information, Kimura (1993) proposed a modeling framework for product and process under a virtual manufacturing point of view.

Thibault et al. (2006) presented a tool called "Ontoforge" to support the integrated design of a forged product considering the knowledge about the process and the information about the system. López-Ortega and Moramay (2005) presented a meta-model using Express-G formalism to include STEP standard in a flexible manufacturing domain.

Bernard et al. (2006) proposed a meta-model structure to link the function/behavior/structure applied to either product, process or resources and external effects.

Colledani et al. (2008) have developed a formalized link between the production system side and the product/process side. Their work proposed a conceptual reference framework for the integrated modeling of product, process and production system data. The framework consists of an object-oriented model developed by means of the UML de-facto standard. The class diagram of this UML model, representing the core of the framework, is described in detail. The conceptual reference framework was developed to support both researchers and industrialists while modeling their problem solving methodologies. The basic idea is that a more effective use of heterogeneous decision support methods at different enterprise levels can be obtained if these methods are based on a common conceptual model. The authors have proposed also two initial applications of the reference framework; one of these applications is about manufacturing system design and represents an earlier proposal of the data formalization presented in Sect. 4.3. The work by Colledani et al. (2008) has partly inspired the data structure presented in this chapter but the latter has been further developed focusing the attention on the manufacturing system side and introducing the concept of evolution.

4.3 Data Formalization for Manufacturing System Design

The system design process plays a key role in defining the overall performance of competitive manufacturing systems having to face the trade-off between productivity and flexibility. The problem consists of designing the optimal system configuration, i.e. the number and type of resources needed to properly satisfy the demand. Technological requirements of the part types to be produced have a major impact on the selection of the types of resources to be adopted, while the production volume requirements influence mainly the choice of the number of resources (Tolio and Valente 2006). The system configuration and reconfiguration problem requires a data structure not only to describe an existing system but also to formalize the elements that can be added (removed) to (from) the reconfigured system.

An effective support tool needs a complete and precise data formalization. For this purpose, a reference framework has been developed by adopting the UML Class Diagram formalism (Fig. 4.1).

The class diagram in Fig. 4.1 shows three main areas: Product, Production System and Process.

In the Product area, the technological and demand characteristic of the product are described. The following classes have been defined:

- Workpiece;
- Machining Feature;
- Scenario Node;
- Production Problem.

In the Production System area the resources and the system characteristics are defined. Since in all this book the attention is centered on Focused Flexibility Manufacturing Systems (FFMS) and on Flexible Manufacturing Systems (FMS), the system resources can be machines, carriers, tool carriers, load/unload stations and pallets. Data related to the manufacturing system and its components are detailed by the following classes:

- System;
- Selected System;
- Hyperplane;

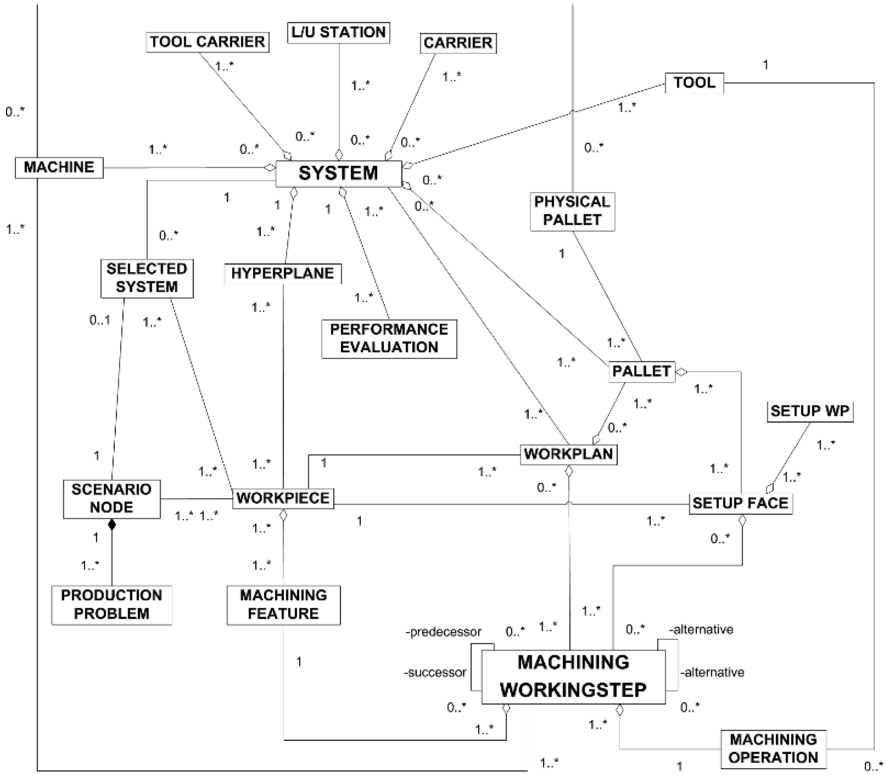

Fig. 4.1 UML class diagram

- Machine;
- Carrier;
- Load/Unload Station;
- Physical Pallet;
- Tool;
- Tool Carrier;
- Performance Evaluation.

The Process area describes, by means of the following classes, how the production system can produce the products:

- Machining Operation;
- Machining Workingstep;
- Workplan;
- Pallet;
- Setup Face;
- Setup WP.

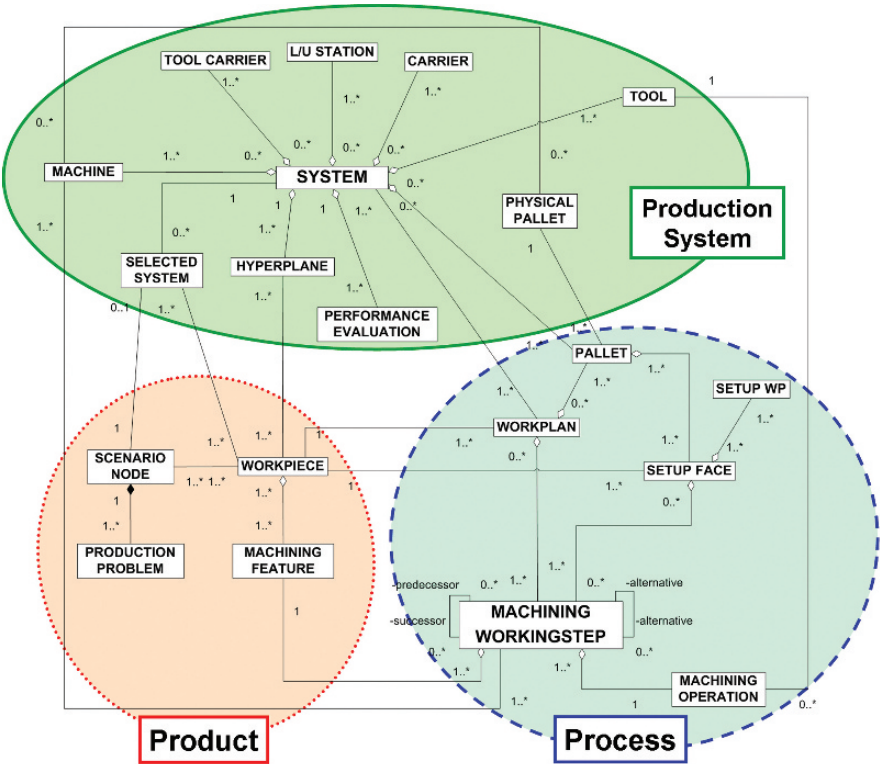

Fig. 4.2 Areas of the UML diagram

These three areas have been highlighted in the UML Class Diagram as shown in Fig. 4.2.

The following sections describe all these classes and their attributes.

4.4 Product

The "Product Area" (dotted line in Fig. 4.2) consists of the Workpiece (Table 4.1; Fig. 4.3), Machining Feature (Table 4.2; Fig. 4.4), Scenario Node (Table 4.3) and Production Problem (Table 4.4) classes; the first two classes are partially derived from the STEP-NC standard (ISO 14649). Each instance of the Workpiece class is one of the part types produced by the system and is related to the codes which can be ordered by the customers.

Each Workpiece is characterized by a set of Machining Features (Table 4.2), i.e. geometric modifications which are realized by machining operations

Table 4.1 Workpiece

Attribute name	Attribute definition
id_workpiece	Workpiece type identifier
its_material	Workpiece type material
global_tolerance	Workpiece type general tolerance
its_rawpiece_geometry	Workpiece type raw piece geometry
its_geometry	Final geometry of the workpiece type
x_bounding_pos	Positive coordinate along x-axis of bounding geometry
x_bounding_neg	Negative coordinate along x-axis of bounding geometry
y_bounding_pos	Positive coordinate along y-axis of bounding geometry
y_bounding_neg	Negative coordinate along y-axis of bounding geometry
z_bounding_pos	Positive coordinate along z-axis of bounding geometry
z_bounding_neg	Negative coordinate along z-axis of bounding geometry
pen_out_cost	Penalty related to missing production; it can figure as an extra cost if outsourcing is adopted
ru_coeff	Product ramp-up coefficient

starting from the raw piece. According to ISO14649, there are different types of feature. Among them the most important are: planar face, pocket, slot, step, hole, generic feature and compound feature.

The workpiece demand is affected by both mid-term and long-term variability. Long-term variability is modeled through the “Scenario Node” class which contains the demand evolutionary data according to a scenario tree representation. Since the production problem resulting from the combination of many products can be pretty hard to manage under an evolutionary perspective, the scenario tree representation (Fig. 4.5) has been adopted to simplify the problem formulation (Ahmed et al. 2003). Each scenario node is characterized by a realization probability and keeps a set of production problems inside. Indeed, mid-term variability is modeled by the “Production Problem” class (Table 4.4) whose instances are production contexts that a manufacturing system should be in principle able to satisfy without requiring a major reconfiguration. One Scenario Node explodes into one or more Production Problems (Fig. 4.5).

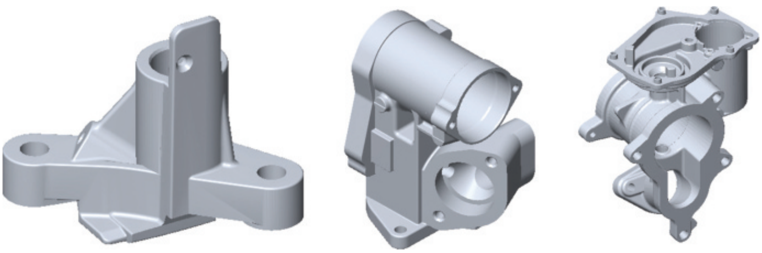

Fig. 4.3 Workpiece examples

Table 4.2 Machining feature

Attribute name	Attribute definition
id_feature	Identifier
its_workpiece	The workpiece type which the feature is part of
its_operations	The set of (machining) operations required to manufacture the feature. In this set of operations there can be alternative operations; for example, if a feature can be machined on two different machines then it is likely that the machines require a different operation (e.g. different cutting speed, feed, etc.)
abstract_supertype	The type of feature (e.g. planar_face, pocket, slot, step, round_hole, toolpath_feature, profile_feature, boss, spherical_cap, rounded_end, thread)
placement_location_x	Position of the feature along the x-axis in the workpiece coordinate system
placement_location_y	Position of the feature along the y-axis in the workpiece coordinate system
placement_location_z	Position of the feature along the z-axis in the workpiece coordinate system
cos_x	Cosine of the angle between the feature working direction and the x-axis of the workpiece coordinate system
cos_y	Cosine of the angle between the feature working direction and the y-axis of the workpiece coordinate system
cos_z	Cosine of the angle between the feature working direction and the z-axis of the workpiece coordinate system

Both Scenario Node class and Production Problem class play a key role in the data model because they transform the framework from static and deterministic to dynamic and stochastic (see Sects. 7.3 and 7.4.1).

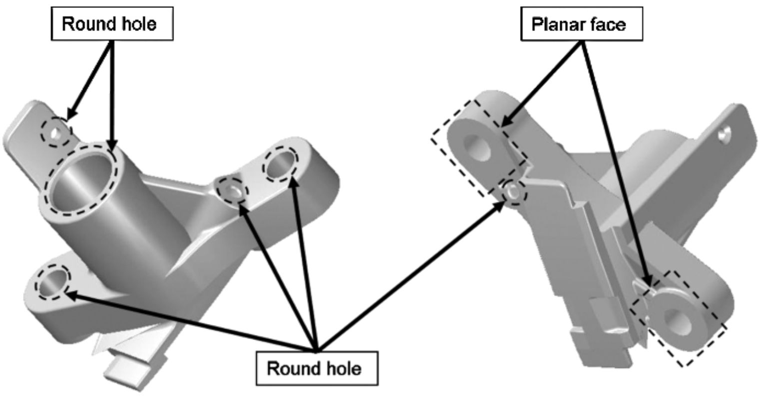

Fig. 4.4 Machining feature spotting

Table 4.3 Scenario node

Attribute name	Attribute definition
id_scenario_node	Node identifier
id_parent_node	Parent node identifier
time_stage	Node time stage
time_step	Time period length which the demand is referred to (the length is the same for the nodes of the same time stage)
probability	Realization probability
mean_part_mix_demand	Mean demand volume of the workpieces in the scenario node
min_demand	Minimum demand volume of the workpieces in the scenario node
max_demand	Maximum demand volume of the workpieces in the scenario node
min_agg	Minimum value of the aggregate demand volume in the scenario node
max_agg	Maximum value of the aggregate demand volume in the scenario node
budget	Budget of the system user that is available for investment in a new system configuration
discount_rate	Discount rate associated with the node. It can be seen as a measure of risk as perceived by the system user

Table 4.4 Production problem

Attribute name	Attribute definition
id_prodprob	Production problem identifier
id_scenario_node	Identifier of the scenario node which the production problem belongs to
part_mix_demand	Demand of the workpieces in the production problem

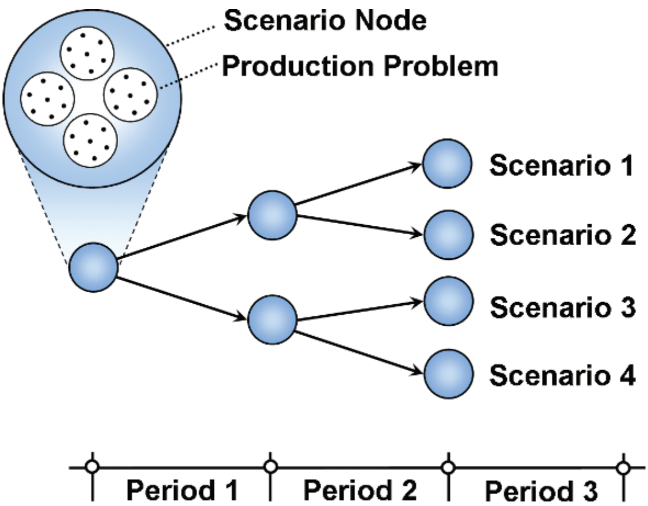

Fig. 4.5 Scenario tree

4.5 Production System

In the “Production System Area” (continuous line in Fig. 4.2), the architectural characteristics of the manufacturing system are detailed. The System class (Table 4.5) is crucial since the definition of the system configuration is the final goal of the whole data formalization process and the system design problem itself. The system configuration is the technical solution proposed by a machine tool builder; this configuration can modify an existing system or define a new manufacturing system from “green field”.

The dynamics of the manufacturing system configuration can be also represented thanks to the “previous_system” attribute, which links a given system with its previous configuration. The link between the system configuration and the addressed production context is represented by the Selected System class (Table 4.6) which holds the decisions taken by the system user about the planning of the system capacity. The Selected System attributes detail which system configuration is chosen to face a particular Scenario Node and how the system configuration performs when facing that context (see Chap. 8).

Table 4.5 System

Attribute name	Attribute definition
id_system	System configuration identifier
previous_system	Previous system configuration identifier
lead_time	Lead time from the order issue to the installation of the new system configuration
inv_cost	Investment cost of the new system configuration (i.e. the commercial bid of the machine tool builder)
op_cost	Operating cost of the system configuration
machine_N	Number of machines for each machine type in the system configuration
carrier_N	Number of carriers in the system configuration
Lustation_N	Number of L/U stations in the system configuration
pallet_N	Number of pallets for each pallet type in the system configuration
tool_N	Number of tools for each tool type in the system configuration
open_time	Daily opening time of the system
workplans	Set of workplans that are processed in the system
ru_coeff	System ramp-up coefficient
sat_conf	Resource type saturation (value estimated by the system configuration activities)
sat_sim	Resource type saturation (value estimated using simulation)
vol_conf	Production volume of the system configuration in a scenario node (value defined by the system configuration activities)
vol_plan	Production volume of the system configuration in a scenario node (value defined by capacity planning activities)
vol_sim	Production volume of the system configuration in a scenario node (value estimated using simulation)
vol_plan_miss	Missing production volume of the system configuration in a scenario node (value estimated by capacity planning activities)

Table 4.6 Selected system

Attribute name	Attribute definition
id_system	Selected system configuration identifier
root_node	Identifier of the scenario node which is the root of the considered scenario tree
time_stage	Time stage during which the system configuration must be implemented
penalty	Penalty related to missing production; it can be an extra cost if outsourcing is adopted

A System configuration is characterized by the possible combinations of production volumes that the system can yield. This property is modeled by the class Hyperplane (Table 4.7). The instances of Hyperplane represent the hyperplanes which are required to mathematically define the admissible production domain of the system configuration (see Sect. 7.4.4).

The System is composed its physical resources: Machines (Table 4.8), Carriers (Table 4.9), Load/Unload Stations (Table 4.10), Tools (Table 4.11), Tool Carrier (Table 4.12) and Physical Pallets (Table 4.13). A Physical Pallet is the element consisting of various sub-elements (table, fixture, etc.) on which the workpieces are mounted and that enters the machine to execute the machining operations (see Sect. 7.4.2).

The instances of the previous classes are either the types of resources composing the current system configuration or the types of resources which are available in the catalogue of the machine tool builder. Their attributes consist of the technological, physical and cost characteristics.

Moreover, the Performance Evaluation class (Table 4.14) has been put into the model to define which system configurations must be evaluated. In this book the performance of the system are evaluated through the simulation technique (see Chap. 9), therefore the attributes of the class have been defined accordingly.

Table 4.7 Hyperplane

Attribute name	Attribute definition
id_hyperplane	Hyperplane identifier
id_system	Identifier of the system which the Hyperplane is related to
id_resource	Resource type which the Hyperplane is related to
resource_N	Number of resources for each resource type (e.g. machine, carrier, etc.) in each system configuration
rhs	Right hand side, i.e. total capacity of the resource type
hyper_coef	Coefficients of the hyperplanes defining the admissible domain of the system configuration
operator	Operator of the constraint: GT = greater than, GE = greater or equal, E = equal, LT = less than, LE = less or equal
work_cost	Production cost for each resource

Table 4.8 Machine

Attribute name	Attribute definition
id_machine	Machine type identifier
avail	Daily availability of the machine type
investment_cost	Investment cost of the machine type
axis_number	Number of controlled axes in the machine
axis_characteristics	Characteristics of the axes of the machine
dim_x	Dimension x of the machine type [mm]
dim_y	Dimension y of the machine type [mm]
dim_z	Dimension z of the machine type [mm]
wcube_x	Work cube dimension along x-axis [mm]
pos_trav_x	Positive travel along x-axis [mm]
neg_trav_x	Negative travel along x-axis [mm]
speed_x	Speed in rapid movement along x-axis [mm/min]
accel_x	Acceleration in rapid movement along x-axis [mm/s^2]
wcube_y	Work cube dimension along y-axis [mm]
pos_trav_y	Positive travel along y-axis [mm]
neg_trav_y	Negative travel along y-axis [mm]
speed_y	Speed in rapid movement along y-axis [mm/min]
accel_y	Acceleration in rapid movement along y-axis [mm/s^2]
wcube_z	Work cube dimension along z-axis [mm]
pos_trav_z	Positive travel along z-axis [mm]
neg_trav_z	Negative travel along z-axis [mm]
speed_z	Speed in rapid movement along z-axis [mm/min]
accel_z	Acceleration in rapid movement along z-axis [mm/s^2]
pos_trav_B	Positive travel around B-axis [degree]
neg_trav_B	Negative travel around B-axis [degree]
speed_B	Speed in rapid movement around B-axis [round/min]
accel_B	Acceleration in rapid movement around B-axis [degree/s^2]
pos_trav_tilting	Positive travel around tilting-axis [degree]
neg_trav_tilting	Negative travel around tilting-axis [degree]
speed_tilting	Speed in rapid movement around tilting-axis [round/min]
accel_tilting	Acceleration in rapid movement around tilting-axis [round/s^2]
power	Maximum machine power [kW]
spindle_speed	Maximum spindle speed [rounds/min]
efficiency	Machine efficiency (necessary to calculate usable power)
tool_change_time	Time to change a tool on the machine type [min]
rotation_time	Shuttle rotation time [min]
tool_magazine	Number of slots in the tool magazine
failure_interval_type	Distribution of the time between failures
failure_interval_mean	Mean time between failures
failure_interval_stdev	Standard deviation of time between failure
repair_interval_type	Repair time distribution
repair_interval_mean	Mean repair time
repair_interval_stdev	Standard deviation of repair times
operation_family	Operation family that the machine can execute (0 = prismatic; 1 = rotational)
precision_level	Precision level of the machine (0 = roughing; 1 = finishing)

Table 4.8 (continued)

Attribute name	Attribute definition
x_pallet	Position of the origin of the pallet coordinate system along the x-axis of the machine coordinate system
y_pallet	Position of the origin of the pallet coordinate system along the y-axis of the machine coordinate system
z_pallet	Position of the origin of the pallet coordinate system along the z-axis of the machine coordinate system
pallet_dim	Dimension of the pallet table which can be loaded on the machine

Table 4.9 Carrier

Attribute name	Attribute definition
id_carrier	Carrier type identifier
investment_cost	Investment cost a unit of carrier
avail	Carrier daily availability
speed_carrier	Carrier speed [m/min]
LU_time_carrier	Time to load/unload a pallet from the carrier [min]

Table 4.10 Load/unload station

Attribute name	Attribute definition
id_LUstation	Load/unload station type identifier
investment_cost	Investment cost for a unit of Load/unload station
avail	Daily availability of the load/unload station
operators	Number of operators working on the load/unload station
buffer	Number of slots in the load/unload station buffer
pallet_dim_min	Minimum dimension of the pallet that can be loaded
pallet_dim_max	Maximum dimension of the pallet that can be loaded

Table 4.11 Tool

Attribute name	Attribute definition
id_tool	Tool type identifier
life	Tool life [min]
regeneration_time	Regeneration time [min]
diameter	Tool diameter [mm]
length	Length of the cutting edge [mm]
tool_length	Length of the tool [mm]
investment_cost	Investment cost for each unit

Table 4.12 Tool carrier

Attribute name	Attribute definition
id_tool_carrier	Tool carrier type identifier
speed_tool	Tool carrier speed
LU_time_tool	Load/unload time
LU_time_tool_central	Load/unload time from central magazine
investment_cost	Investment cost for each unit

Table 4.13 Physical pallet

Attribute name	Attribute definition
id_physical_pallet	Physical pallet type identifier
dim_x	Table dimension along x-axis [mm]
dim_y	Table dimension along y-axis [mm]
dim_z	Table dimension along z-axis [mm]
fix_dim_x	Fixture dimension along x-axis [mm]
fix_dim_y	Fixture dimension along y-axis [mm]
fix_dim_z	Fixture dimension along z-axis [mm]
investment_cost	Investment cost for each unit

Table 4.14 Performance evaluation

Attribute name	Attribute definition
id_simulation	Simulation run identifier
id_system	Identifier of the system to be evaluated through simulation
id_scenario_node	Identifier of the scenario node to be evaluated through simulation
replicates	Number of replicates
length	Length of the run [min]
warmup	Length of the warm-up period [min]

4.6 Process

The "Process Area" (dashed line in Fig. 4.2) describes how the system resources can be used to machine the workpieces. The Machining Operation (Table 4.15), Machining Workingstep (Table 4.16) and Workplan (Table 4.17) classes are partially derived from STEP-NC standard.

Instances of the Machining Operation class describe the machining processes, specifying the tool to be used and a set of technological parameters.

Table 4.15 Machining operation

Attribute name	Attribute definition
id_operation	Machining operation identifier
retract_plane	The height of the retract plane associated with the operation
its_tool	Identifier of the tool that must be used for this operation
feederate	Feedrate of the tool. The feed rate specified applies to the motion of the tool center point
cutspeed	Cutting speed
coolant	Coolant options
spindle_speed	Required spindle speed [rounds/min]
power	Required power [kW]
operation_type	Operation type (e.g. milling, drilling, turning, etc.)
operation_family	Operation family which the operation belongs to (0 = prismatic; 1 = rotational)
precision_level	Precision level of the machining operation (0 = roughing; 1 = finishing)

Table 4.16 Machining workingstep

Attribute name	Attribute definition
id_workingstep	Machining workingstep identifier
its_feature	The manufacturing feature upon which the machining workingstep operates
its_operation	The operation which will be performed upon the machining feature
its_effect	The change to the geometry of the workpiece caused by the operation. A CAM system can use this attribute to describe the predicted effect of this operation on the geometry of the workpiece
its_secplane	The security plane for the machining workingstep. On or above this plane, i.e. for z-value greater than this, a safe movement of the tool without danger of collision is possible
ws_cutting_time	Cutting time of the machining workingstep
its_tool_direction	Tool direction
machine_set	Set of machine types where the machining workingstep can be processed
alternative_ws	Set of alternative machining workingsteps
Predecessor	Set of machining workingsteps that are predecessors of the described machining workingstep
Together	Set of machining workingsteps that must be processed together (i.e. on the same pallet and same machine) with the described machining workingsteps

Instances of the Machining Workingstep class represent the machining process for a specific machining feature; a machining workingstep defines the association between a distinct feature and an operation to be performed on the feature. As the related operation, the machining workingstep is characterized by the use of a single tool and a set of technological parameters which are usually constant during the application of the machining workingstep. During the machining workingstep, no tool change is allowed.

Compared to the STEP-NC approach, the Machining Workingstep class shows also the “ws_cutting_time” attribute and the “machine_set” attribute. The “ws_cutting_time” attribute defines the machining time needed to complete the workingstep, while the “machine_set” attribute represents the set of machine types which can process the machining workingstep.

Process constraints are defined among the instances of the machining workingstep class.

Table 4.17 Workplan

Attribute name	Attribute definition
id_workplan	Workplan identifier
id_workpiece	Workpiece type processed with the described workplan
workingsteps	Set of machining workingsteps needed to complete the workplan
pallets	Set of pallets with an execution sequence needed to complete the workplan

Table 4.18 Pallet

Attribute name	Attribute definition
id_pallet	Pallet identifier
LU_time_type	Distribution of the time to load/unload all the parts on/from a pallet
LU_time_mean	Mean time to load/unload all the parts on/from a pallet
LU_time_stdev	Standard deviation of the load/unload time
physical_pallet	Identifier of the physical pallet type related to the pallet type
N_parts	Number of parts mounted on the pallet
N_setupface	Number of faces on the fixture of the pallet
machine_set	Set of machines where the pallet can be loaded
x_setupface	Origin of the setup faces along the x-axis in the pallet coordinate system
y_setupface	Origin of the setup faces along the y-axis in the pallet coordinate system
z_setupface	Origin of the setup faces along the z-axis in the pallet coordinate system

A Workplan (Table 4.17) is defined as a collection of Machining Workingsteps together with an execution sequence. Moreover, a Workplan can be seen also as an ordered sequence of Pallet types. A Pallet type (Table 4.18) is the logical element that defines how a Physical Pallet (Table 4.13) can be used to process the workpieces. The workpieces are clamped on fixtures that are mounted on the Physical Pallets. Each fixture consists of one or more faces (Fig. 4.6). The Setup Face class (Table 4.19) defines which is the setup (i.e. the orientation) of the workpieces, while the Setup WP class (Table 4.20) defines the locations of the workpieces on the face.

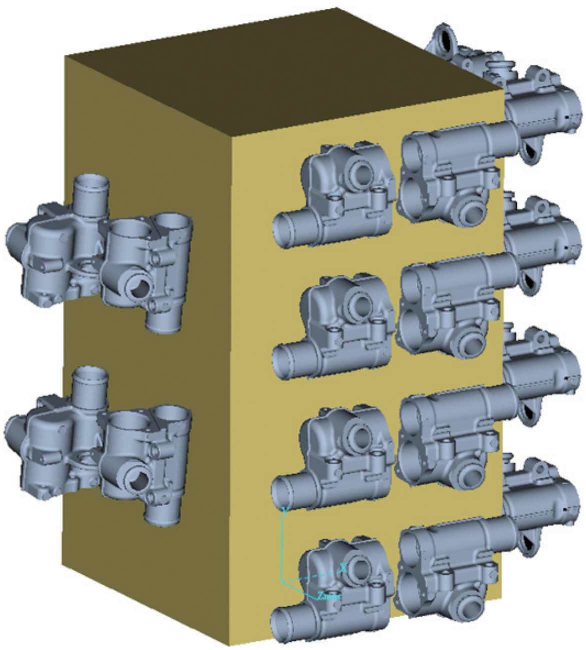

Fig. 4.6 An example of tombstone fixture with four faces

Table 4.19 Setup face

Attribute name	Attribute definition
id_setup_face	Setup Face identifier
pallet	Set of pallet types where the setup face is present
N_parts	Number of parts that are mounted on the setup face
workpiece	The workpiece type which is processed on the setup face. It is assumed that a setup face can have only one workpiece type (see Sect. 6.3)
workingsteps	Set of machining workingsteps machined on the setup face
rapid_time	Total rapid time to process a machining workingstep on all the workpieces which are mounted on a setup face. Rapid time depends on the machine where the machining workingstep is executed
cos_xx	Cosine of the angle between the x-axis of the workpiece coordinate system and the x-axis of the machine coordinate system
cos_xy	Cosine of the angle between the x-axis of the workpiece coordinate system and the y-axis of the machine coordinate system
cos_xz	Cosine of the angle between the x-axis of the workpiece coordinate system and the z-axis of the machine coordinate system
cos_yx	Cosine of the angle between the y-axis of the workpiece coordinate system and the x-axis of the machine coordinate system
cos_yy	Cosine of the angle between the y-axis of the workpiece coordinate system and the y-axis of the machine coordinate system
cos_yz	Cosine of the angle between the y-axis of the workpiece coordinate system and the z-axis of the machine coordinate system
cos_zx	Cosine of the angle between the z-axis of the workpiece coordinate system and the x-axis of the machine coordinate system
cos_zy	Cosine of the angle between the z-axis of the workpiece coordinate system and the y-axis of the machine coordinate system
cos_zz	Cosine of the angle between the z-axis of the workpiece coordinate system and the z-axis of the machine coordinate system

Table 4.20 Setup WP

Attribute name	Attribute definition
id_setup	Setup WP identifier
workpiece	The workpiece type which the setup wp is related to
x_setupwp	Position of the setup wp along the x-axis of the setup face coordinate system
y_setupwp	Position of the setup wp along the y-axis of the setup face coordinate system
z_setupwp	Position of the setup wp along the z-axis of the setup face coordinate system
setupface	Setup face which the setup wp is related to
n_row	Number of rows on the setup face
n_col	Number of columns on the setup face
d_row	Distance between two workpieces on the same row
d_col	Distance between two workpieces on the same column

4.7 Implementation

The implementation of the data formalization model described above is a key aspect to be considered, since the proposed framework aims at real industrial world applications. This kind of data formalization model can be represented through both a relational database and an ontology. A database can give a more concrete and specific vision of the world, while an ontology is used to create a conceptual model of the world; a database focuses on the instances, while an ontology on the entities. Moreover, an ontology can be analyzed by "reasoning" methods which can help to extend the knowledge.

During the work, it was decided to adopt a relational database implementation in order to guarantee an easier integration and data exchange among the modules composing the system design architecture. The relational database has been implemented using MS Access. An abstract of tables and relations of the database is reported in Fig. 4.7.

The link between the data formalization classes and the database is shown by the following tables: product data (Table 4.21), resource data (Table 4.22), process data (Table 4.23), link between machine and process (Table 4.24), resources in the system configuration (Table 4.25), process in the system configuration (Table 4.26), performance of the system configuration (Table 4.27) and capacity plan (Table 4.28). It can be noted that implementing a relational database requires a large number of relations to be made explicit.

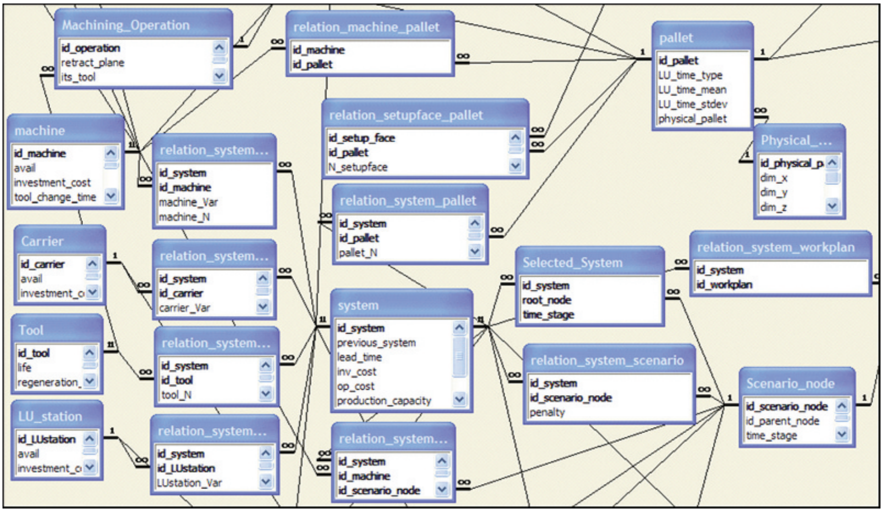

Fig. 4.7 Database relations

Table 4.21 Product data

Database table	Related classes
Workpiece	Workpiece
Machining_Feature	Machining Feature
Scenario_node	Scenario Node
Production_Problem	Production Problem
relation_feature_workpiece	Machining Feature, Workpiece
relation_workpiece_scenario	Workpiece, Scenario Node
relation_workpiece_problem	Workpiece, Production Problem

Table 4.22 Resource data

Database table	Related classes
Machine	Machine
Carrier	Carrier
LU_station	Load/Unload Station
Tool	Tool
Tool_carrier	Tool Carrier
Physical_Pallet	Physical Pallet

Table 4.23 Process data

Database table	Related classes
Machining_Operation	Machining Operation
Machining_Workingstep	Machining Workingstep
Pallet	Pallet, Physical Pallet
Setup_Face	Setup Face
Setup_WP	Setup WP
Workplan	Workplan
relation_feature_operation	Machining Feature, Machining Operation
relation_workplan_workingstep	Workplan, Machining Workingstep
relation_workplan_pallet	Workplan, Pallet
relation_workpiece_pallet	Workpiece, Pallet
relation_setupface_workingstep	Setup Face, Machining Workingstep
relation_setupface_setupWP	Setup Face, Setup WP
relation_setupface_pallet	Setup Face, Pallet
relation_workingstep_workingstep	Machining Workingstep
relation_workingstep_together	Machining Workingstep
relation_workingstep_predecessor	Machining Workingstep

Table 4.24 Link between machine and process

Database table	Related classes
relation_machine_setupface	Machine, Setup Face
relation_machine_pallet	Machine, Pallet
relation_machine_workingstep	Machine, Machining Workingstep
relation_machine_workingstep_pallet	Machine, Machining Workingstep, Pallet

Table 4.25 System configuration: resource data

Database table	Related classes
System	System
relation_system_machine	System, Machine
relation_system_Lustation	System, Load/unload Station
relation_system_carrier	System, Carrier
relation_system_pallet	System, Pallet
relation_system_tool	System, Tool
relation_system_toolcarrier	System, Tool Carrier

Table 4.26 System configuration: process data

Database table	Related classes
relation_system_workplan	System, Workplan
relation_system_machine_pallet	System, Machine, Pallet
relation_system_machine_workingstep	System, Machine, Machining Workingstep
relation_system_machine_workingstep_pallet	System, Machine, Machining Workingstep, Pallet

Table 4.27 System configuration: performance data

Database table	Related classes
relation_system_carrier_scenario	System, Carrier, Scenario Node
relation_system_LUstation_scenario	System, Load/unload Station, Scenario Node
relation_system_machine_scenario	System, Machine, Scenario Node
relation_system_pallet_scenario	System, Pallet, Scenario Node
relation_system_workpiece_scenario	System, Workpiece, Scenario Node
relation_system_scenario	System, Scenario Node
Simulation	Performance Evaluation, System, Scenario Node

Table 4.28 System configuration: capacity plan

Database table	Related classes
Selected_System	Selected System
Hyperplane	Hyperplane
relation_workpiece_hyperplane	Workpiece, Hyperplane

4.8 Conclusions

The development of a common data structure for all the activities related to the design of manufacturing systems offers various benefits because it allows the integration of modules, tackling the different sub-problems, that are strongly linked by data exchange. The concept of evolution has been stressed since this kind of information must be provided to methodologies aiming at planning the life-cycle of a manufacturing system in an uncertain environment.

Even if the proposed data formalization has been developed to face the FMS and FFMS design problem, the work can be easily extended to other manufacturing domains thanks to its flexibility and scalability. In particular, information about demand volumes could be further detailed and aspects closer to production planning and system management could be modeled as well.

Other potential future developments could aim at the creation of an object-oriented database to directly implement the data formalization framework described in this chapter without passing through a relational database. For example, an ontology about manufacturing could be realized following the object-oriented model.

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Chapter 5
Manufacturing Strategy: Production Problem Analysis for Assessing Focused Flexibility

Manfredi Bruccoleri, Diego Lanza and Giovanni Perrone

Abstract The objective of this chapter is to define an operationalization pattern which supports decision makers and managers in determining the level of manufacturing flexibility competences, given the business strategy and the manufacturing structure of the firm. This should drive the production system design and configuration activity. Specifically, this chapter presents an innovative approach to develop a manufacturing strategy, which is based on the idea that information on potential production problems that the manufacturing system could face throughout a given long-term planning horizon should be used as a starting point to determine the level of flexibility that the system should possess.

Keywords Manufacturing strategy · Focused flexibility · Product life-cycle

5.1 Introduction

As discussed in the introduction of this book, the recent competitive scenario, characterized by decreasing product life-cycles, market globalization, customized product requirements, and high demand uncertainty, has pushed manufacturing firms more toward the adoption of flexible manufacturing systems in order to achieve high levels of reactivity against future scenario uncertainty rather than traditional manufacturing solutions like transfer lines. On the other hand, in order to overcome the limits of flexible manufacturing system solutions (i.e. the high investment cost for their acquisition and the low capacity factor), academic research (Koren et al. 1999) and R&D departments of some machine tool builders as Cincinnati Machine, Lamb Technicon Machining Systems and Masco Machine (John Teresko 2002) have recently introduced the new concept of Reconfigurable Manufacturing Systems (RMSs). These are a mid-span

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solutions between FMS and dedicated manufacturing systems, like transfer lines, and provide properties of scalability (i.e. the capability to easily change the production maximum capacity) and customized flexibility (i.e. the capability to perform a certain class of technological operations within a given part family). In other words, RMS is a manufacturing system with customized flexibility while FMS is a manufacturing system with general flexibility (Hu 2005; Hu et al. 2006). Scalability and customized flexibility are enabled by reconfigurable machine tools that are designed since the beginning for having a modular structure. This structure is initially configured for manufacturing a given number of part types at a certain production rate and is also suitable for being reconfigured by adding or subtracting machining or equipment modules in order to process other types of technological operation ("similar" to the previous ones) and/or work with a different production rate. Thus, both scalability and customized flexibility are strictly tied to the design of machine tools and the related industry technology innovation rate. Reconfigurable machine tools (RMTs) are an essential enabler for RMSs. However, the current state-of-the-art does not allow broadly reconfigurable machine tools to be available as the required technology is still back in various states of development (ElMaraghy 2005).

Recent research studies highlight manufacturing systems designed by focusing the flexibility degree (FFMSs) could represent a strategic answer to production contexts characterized by demand changes. The flexibility customization is achieved by the hybrid architecture in which both general purpose and dedicated resources could be selected. In fact, system flexibility can be related to the flexibility of each single selected resource as well as the interaction among the resources composing the system. For instance, a flexible system can be composed of dedicated machines and highly flexible carriers (Tolio and Valente 2007). FFMS strategic design decisions involves two sets of options: (a) design a dedicated system in which the reconfiguration option can be implemented when production changes occur (similarly to the RMS solution); (b) purchase more flexibility than the amount strictly required by the current 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 part families (Tolio et al. 2007).

Therefore, from manufacturing strategy standpoint, the strategic design of the manufacturing system becomes more complex because it should also consider the definition of a flexibility domain and evaluate whether the focused flexibility solution is more efficient than FMSs or rigid systems. Specifically, the strategic design phase aims at addressing manufacturing system strategic variables based on enterprise competitive scenario, marketing strategies, financial and economics constraints and risk propensity. These variables consist of flexibility forms (mix flexibility, technology flexibility, volume flexibility, expansion flexibility and so forth), competitive policies (production mix and volumes etc.), "make or buy" strategies, and an estimation of the long-term capacity to be installed over a time horizon equal to the system life-cycle.

The scientific literature on operations strategy shows that converting business strategy into manufacturing strategy and manufacturing strategy into flexibility competences is a very complex issue. This chapter presents some findings from a literature survey on manufacturing strategy vs. manufacturing flexibility and proposes an innovative approach for manufacturing strategy operationalization. It leverages the idea to exploit information on potential production problems as starting point for determining the level of flexibility that the manufacturing system should hold over the time horizon. Starting from this idea, this chapter proposes a methodology for generating a scenario tree of different and potential production problems, given a specific manufacturing strategy and the competitive landscape.

5.2 Research Background and Methodology

A large body of literature deals with the issue of aligning manufacturing strategy with business strategy and with manufacturing system capabilities. Most of the researches usually propose theoretical frameworks for strategic alignment or empirical validations of the impact of being flexible to business performance. However, being flexible to produce many products requires a broader set of manufacturing policies than the case of being flexible to handle brutal volume variations. Moreover, flexibility requires general purpose machines, versatile workers, good information systems and many other elements that raise both initial investment and variable costs. Next, the risk associated with flexibility, as a manufacturing choice, entails a cost-benefit break-even analysis or some other trade-off considerations, which have brought up today to consider customized flexibility as an explicit set of manufacturing system design choices that need to be taken under a specific manufacturing goal. According to Miller and Roth (1994), specifying manufacturing strategy (MS) means defining two core elements:

- the manufacturing goal
- the "pattern of choices" that the manufacturing function should make over time

It seems to be intuitive that the pattern of choices should support the manufacturing goal while it is generally accepted that manufacturing goal should be consistent with the business strategy, as it is embedded in the "strategic fit" principle which has been firstly introduced by Skinner (1969) – he argued that "manufacturing becomes the missing link in corporate strategy". Many strategic management scientific papers deal with the "generic strategies" definition with regard to both the business and manufacturing area. A generic strategy can be considered as a meta-strategy – i.e. a strategic model companies build their specific strategies up on. Generic manufacturing strategies can be described as a common pattern of organizing production, which is identifiable because commonalities occur in the way manufacturers organize their plants in order to achieve manufacturing objectives (Devaraj et al. 2004). The definition of a generic manufacturing strategy depends on choices and decisions to be made throughout the strategy definition that mainly concern the way by which the production is organized on different manufacturing dimensions.

In the generic MS literature, Kotha and Orne (1989) framework is one of the most cited. The framework is graphically represented in Fig. 5.1 and represents the extension of the well-known Hayes and Wheelwright (1984) product-process matrix. Briefly, this framework identifies manufacturing strategies (i.e. goals and decision patterns) by classifying them according to the effects on the manufacturing structure that is represented by three dimensions. The first dimension – process structure complexity – refers to the well known process maturity concept. A complex structure process (mature process), typically used in the production of commodities, is characterized by strong interconnections among processing stages, while an immature process that exhibits many discontinuities in production, as a job shop, would have low process structure complexity. The second dimension – product line complexity – is a measure of the types and variety of product lines. A complex product line refers to product lines complex in design (customized production) while a simple product line refers to the production of commodity-like items. The third dimensions – organizational scope – is intended as the level to which the manufacturing function experiences vertical and horizontal integration of manufacturing operations. Such a dimension is strictly related to the outsourcing degree of low value manufacturing processes and no-core products.

As mentioned, different strategic dimensions can be used for supporting a dominant strategy. The literature shows different models and frameworks that are based on these concepts (Hambrick 1983, Galbraith and Schendel 1983). The approach proposed by Wheelwright (1984) identifies two major dimensions

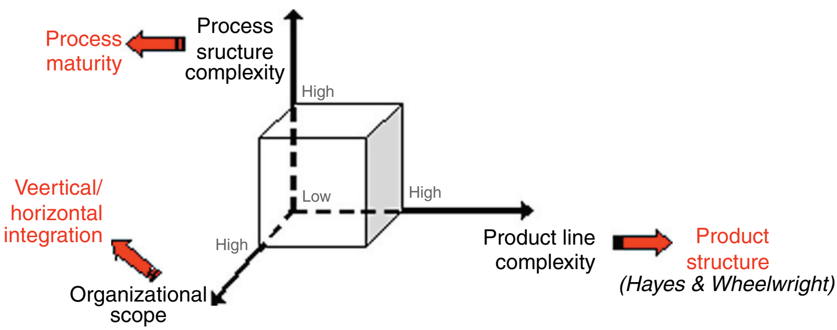


Fig. 5.1 Kotha and Orne (1989) framework

by which the manufacturing function can contribute to the achievement of a given business strategy:

- Market orientation: manufacturing choices need to be responsive to market demand; the system should produce a variety of products and manufacturing processes have to be flexible for producing customized, high quality and low-cost products.
- Technology orientation: manufacturing choices are led by the technology developments more than by the market demand.

The way by which technology affects manufacturing strategic decisions is through automation and process innovation (Williams et al. 1995). Automation affects positively the level of sophistication of quality assurance programs and capacity planning process as well (Anderson et al. 1989). On the other side, process innovation concerns several areas, which influence manufacturing strategic decisions like robotics, materials, CAD-CAM systems, machine tools, etc.

Manufacturing flexibility is the most important area where the manufacturing function supports the market orientation of the firm. As described in Chap. 3, different kinds of flexibility have to be settled for different kinds of customer specifications and requirements. For instance, the abilities to provide high product variety or to change production volumes can be achieved trough higher level of capacity slack or an increased use of general purpose machines (Chase and Aquilano 1992). This consideration is aligned with (Zhang et al. 2003), which argue that technologically advanced firms usually use special purpose machines characterized by low setup, waste and retooling costs. Figure 5.2 summarizes such considerations by setting down a pattern for MS operationalization based on the manufacturing dominant orientations and strategic variables.

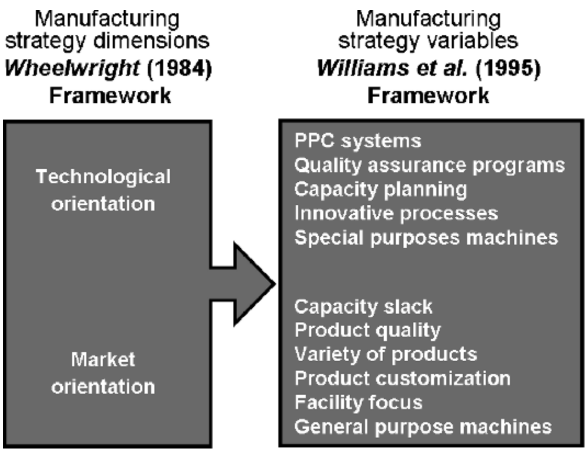


Fig. 5.2 A pattern for MS operationalization based on manufacturing dominant orientations

The literature analysis that has been conducted shows that many theoretical frameworks have been proposed for establishing decisional paths to help managers and production system designers in defining manufacturing system specifications and assessing flexibility choices. The proposed frameworks, however, have to be interpreted from a conceptual perspective. Their practical adoption should involve a complex elaboration which strongly depends on the definition of the manufacturing strategy and the flexibility specification. The main issue concerns the definition of boundaries for the manufacturing function that the term MS and flexibility specifications refer to. As said in the introduction, MS "pattern of choices" deals with making some decisions, along many manufacturing dimensions, about manufacturing resources for achieving some strategic objectives. While restricting the field of dimensions into the manufacturing flexibility dimension surely simplifies the complexity of the problem, it should also be considered that the term manufacturing resource refers to several concepts. Indeed, a resource can be a single machine tool, a whole production system like an FMS or an even complex system such as a multi-plant multi-site system, or the entire value chain including all the resources needed in the product development as well as in the upstream supply chain. In such different scenarios a MS would involve very different decisions. Suppose, for instance, that a given strategic goal would bring the firm to decide whether to or not to invest in volume flexibility. This could mean to implement some outsourcing or sub-contracting strategies (according to a large perspective of the manufacturing function including suppliers and sub-contractors) or some production capacity slacks (when production decisions are limited to manufacturing system). Another example could be a firm whose manufacturing strategic objective is to be technology-oriented. Looking at single machines, this could lead the firm to introduce CNC machining centers while, looking at the whole production system, it could lead to introduce flexible automation in the material handling system (MHS) so enabling the system routing flexibility.

The approach to elaborate manufacturing strategy into the flexibility assessment proposed by this chapter moves from the above considerations and leverages the importance of information on potential production problems to be faced in order to determine the right flexibility degree for the manufactuirng system. The result is a proposal of a framework that has practical implications over the design of focused flexibility manufacturing system.

5.3 MS Operationalization Based on Production Problems Generation

In order to design a focused flexibility production system, it is necessary to have a major insight into the requirements which characterize the production problem. This means to deal with information about maximum quantities of each part to produce, part mix evolution, new part introduction, part removal, and so on. This information represents production constraints that define a production volume domain of heterogeneous family of products that the system must be able to produce over a given planning horizon. The shapes of demand profiles for the different parts to be produced together with information about volume and mix uncertainty at each time step and per part, are the main output from the executing the business strategy process. It is the major information that the manufacturing strategy definition process should use as well, in order to determine some strategic system features as the right flexibility degree.

5.3.1 Scenario Tree Definition

Since the production problem resulting from the combination of many products can be pretty hard to manage in an evolutionary perspective, a scenario tree representation can be adopted to simplify the problem representation (Tolio and Valente 2007).

Evolution for production requirements could be graphically represented by a set of nodes and arcs. Nodes are the potential future states of production requirements, i.e. market demand and technological information of a production mix in a specific time period. Therefore a set of nodes corresponding to different time stages represents a specific scenario of the production requirement evolution process (Ahmed et al. 2003). Arcs are simply the time transition from a manufacturing state to the next one. Main characteristics of a production tree are as follows:

- Random parameters evolve over the system life-cycle according to discrete time stochastic processes;
- Each node of the scenario tree, except the root, has a unique parent, and each non-terminal node is the root of a sub-tree;
- Each node is associated with a probability value.

Consistently with data formalization from Chap. 4, each node (Table 4.3) contains technology data about part mix and probability values. A scenario node is characterized by information concerning:

- Node identifier;
- Parent node identifier;
- Time stage the node belongs to;
- Time step whose length is the time period the demand refers to (the length is the same for the nodes of a given time stage);
- Realization probability;
- Demand volume for each part type.

Moreover, nodes can be characterized by additional information such as budget constraints and financial availability.

5.3.2 Product Life-Cycle

The intrinsic variability of the production problem can lead to different demand evolutions for each product. It is worth evaluating how much the system design process is affected by the demand variability and how much it is necessary to model these uncertainties.

Since the goal is to assess focused flexibility solutions for given manufacturing strategies adapted to specific production problems, it would be reasonable to expect that the FFMS solution be more suitable when the production problem consists of a limited mix of part with medium to high volumes. For such a reason, an example of a real production context (interesting for the Focused Flexibility area) could be typically characterized by:

- parts to be produced by the manufacturing system: these are components of final products that are manufactured or assembled furthermore by another manufacturer or assembler (typically an Original Equipment Manufacturer);
- part volumes evolve following the final product life-cycle, the bill of material quantities and the manufacturing strategy;
- few components types in the part mix;
- product evolution over time: different product versions can be introduced and/or be complementary.

Figure 5.3 shows the product life-cycle shape that can be defined by five *demand parameters* as follows:

1. Increase Start (*IS*)
2. Increase End (*IE*)
3. Decrease Start (*DS*)
4. Decrease End (*DE*)
5. Max height (*V*)

Product life-cycle must respect the growth-maturity-decline shape as Fig. 5.3 shows.

$$IS \leq IE \leq DS \leq DE$$

As described by the following sub-sections, given a planning horizon (T), the parameters describing the demand life-cycle shape over T change depending on the total life-cycle *IS–DE* length, the maturity time interval *IE–DS,* and the planning horizon. Three different cases have been considered:

- Medium life-cycle for $IE\text{-}DS < T < IS\text{-}DE$
- Short life-cycle for $IS\text{-}DE < T$
- Long life-cycle for $IE\text{-}DS > T$

5.3.2.1 Long Life-Cycle

When the product has a long life-cycle, it has been assumed that the maturity time interval is longer than the total planning horizon. In this case five demand

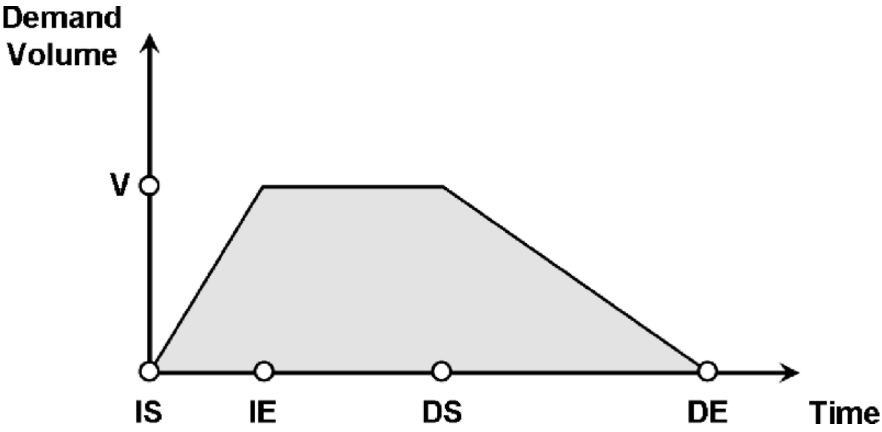


Fig. 5.3 Product life-cycle

profiles – configurations – can be considered (Fig. 5.4) depending on the initial state of the demand profile – i.e. growth stage, maturity stage or decline stage at time zero.

5.3.2.2 Medium Life-Cycle

When the product has a medium life-cycle, the maturity time interval is shorter than the total planning horizon that in turn is shorter than the whole product life-cycle. In this case, four demand configurations can be considered (Fig. 5.5).

5.3.2.3 Short Life-Cycle

In this case, the total life-cycle is shorter than the total planning horizon. Three demand configurations can be considered as shown by Fig. 5.6.

5.3.3 Scenario Tree Generation

The demand evolution over the time horizon can be modeled by a discrete way defining time stages. The number of nodes of production problem scenario tree varies depending on the level of uncertainty related to the product demand evolution. However, it is realistic to assume that some levels of information about the product demand are known at the beginning therefore the structure of the tree can be simplified. Specifically, it is assumed that three kinds of information are known since the beginning of the process:

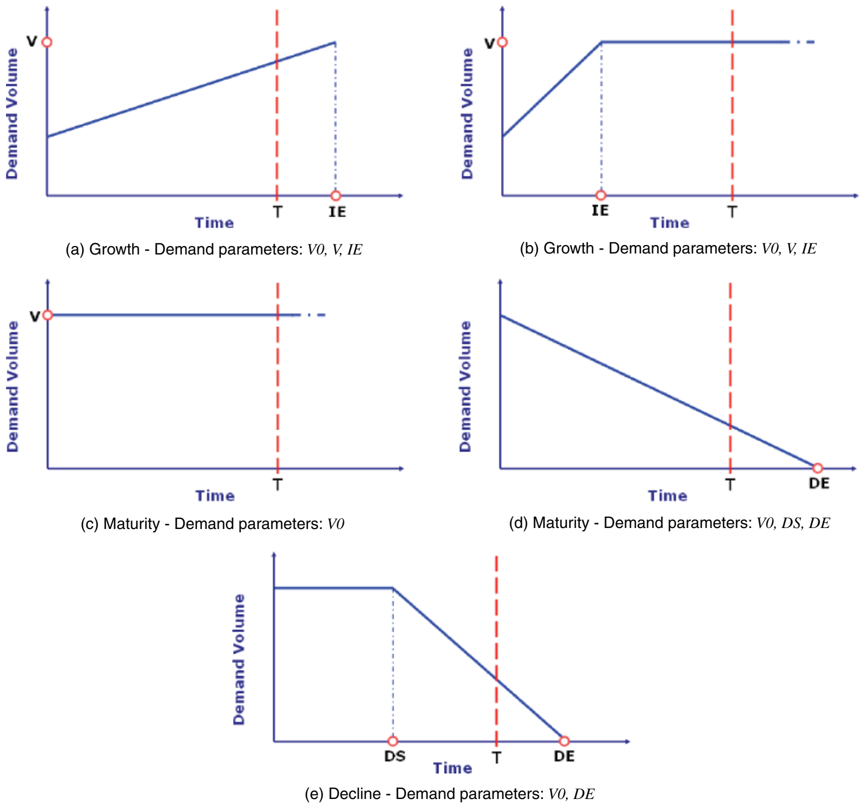
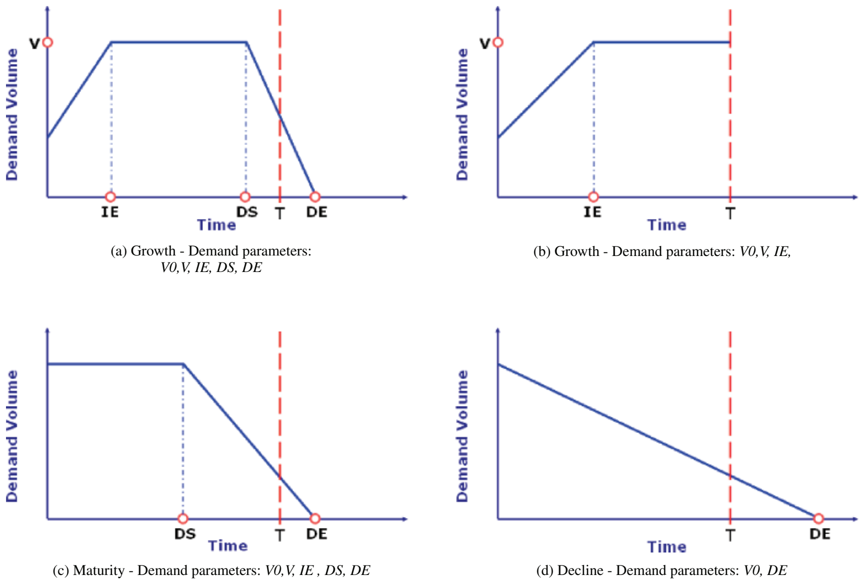


Fig. 5.4 Product long life-cycle: demand profiles when the initial state is growth – (**a**) and (**b**), maturity – (**c**) and (**d**), decline (**e**)

1. the total length of product life-cycle with respect to the planning horizon (long, medium, or short life-cycles);
2. the product demand at time zero (i.e. the current time stage);
3. the demand trend at the initial time stage (growth, maturity or decline).

According to previous sections, this information is very useful to predict what kinds of demand configurations and parameters are necessary to settle on the demand profiles. For instance, if at the first time stage a product with a long life-cycle presents a "growth" trend, it would be reasonable to consider that the demand could either keep growing or settling down to a maturity phase at some point over the planning horizon. In fact, it is likely that the demand profile will not start decreasing as the product has a long life-cycle – i.e. its maturity phase is longer that the planning horizon. In other words, the assumptions that have been considered are very useful to simplify the construction of the possible scenarios as they allow to reject some configurations that would be improbable



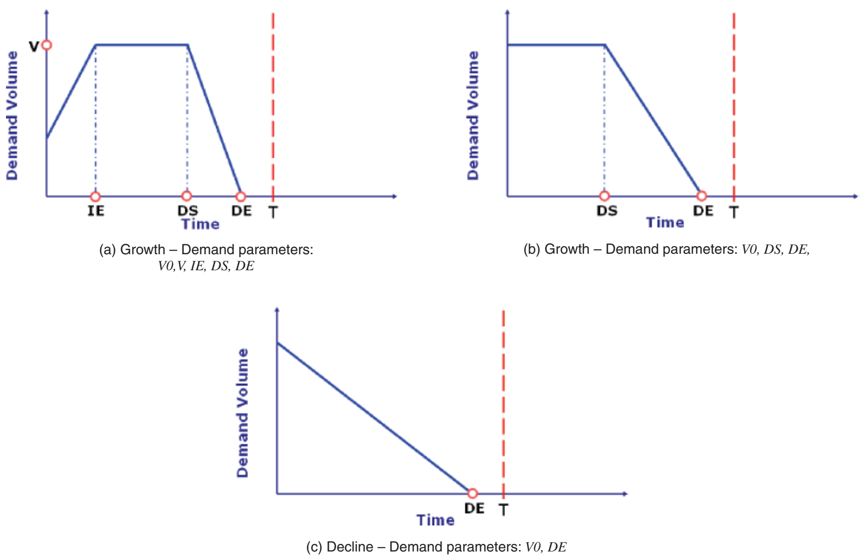
(a) Growth - Demand parameters: *V0,V, IE, DS, DE*

(b) Growth - Demand parameters: *V0,V, IE,*

(c) Maturity - Demand parameters: *V0,V, IE , DS, DE*

(d) Decline - Demand parameters: *V0, DE*

Fig. 5.5 Product medium life-cycle: demand profiles when the initial state is growth – (**a**) and (**b**), maturity (**c**), decline (**d**)



(a) Growth – Demand parameters: *V0,V, IE, DS, DE*

(b) Growth – Demand parameters: *V0, DS, DE,*

(c) Decline – Demand parameters: *V0, DE*

Fig. 5.6 Final product short life-cycle: demand profiles when the initial state is growth (**a**), maturity (**b**), decline (**c**) to happen in a real case. On the other hand, since the nature of the study is explorative and the research has to be considered in a preliminary phase, assumptions and simplified version for the proposed scenario tree structure can be considered acceptable to represent real production problem evolutions. In the mentioned case (long life-cycle and initial phase of growth) for the construction of scenario tree, just two demand configurations in the box of Fig. 5.7 should be considered.

Figure 5.7 represents three possible scenario tree structures associated with the case of product long life-cycle. Indeed, in this case, five different demand configurations have to be taken into account. It can be noticed that, for example, if the initial state is "growth", two possible configurations – otherwise ramifications – have to be considered, each one corresponding to a given occurrence probability (p_1 and p_2), connected to uncertainty through the potential courses of the life-cycle in the planning horizon. Analogously, Fig. 5.8 reports all of the potential scenario tree configurations per product life-cycle length and per initial state trend of product demand.

All of the above considerations support the generation of the scenario three for a given final product. If the scenario tree must be generated for a component and sub-component manufacturer, the final product scenario tree should be translated into the component scenario tree. Once the final product life-cycle has been defined, information on the product bill of material (BoM) will allow determining the component life-cycle shape. The whole scenario tree will be given by the combination of the scenario trees of each component of the part mix.

As already discussed in the previous sections, from a strategic standpoint, the decisions pattern that the manufacturing function should make over time is to be consistent with the business strategy definition (strategic fit). Such choice pattern has to be taken according to the production problem dynamics that the firm wishes to face. The evolution of the production problem depends strictly on the final product demand life-cycles but the actual volumes and part mix evolutions depend on the firm business strategy. As an example, if the firm plans to enter a new market for a limited period of time (e.g. a couple of years)

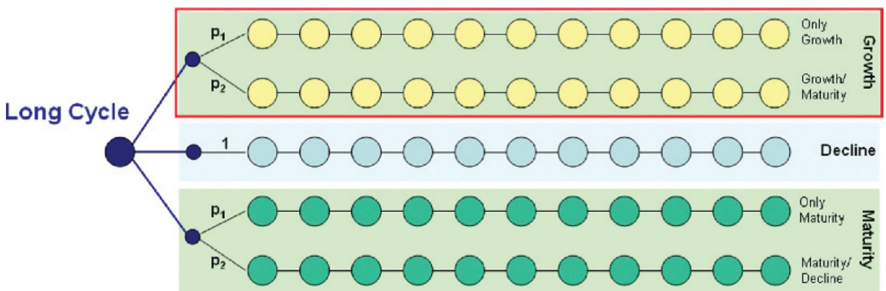


Fig. 5.7 Configuration tree: long life-cycle

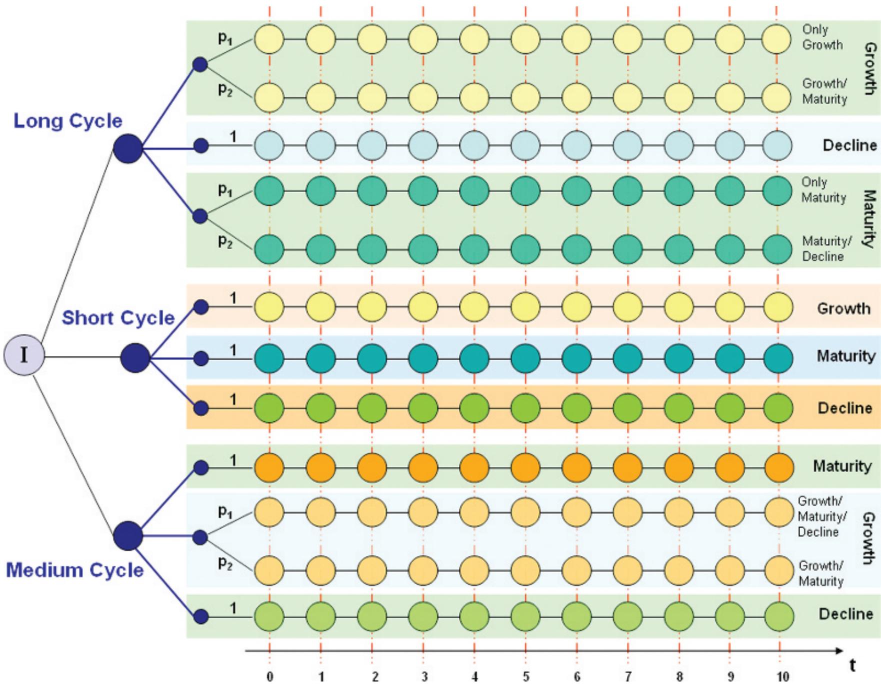


Fig. 5.8 Configuration tree of product life-cycle: the whole tree

by producing a specific component for that period, the production problem that needs to be faced will certainly depend on such a strategic decision besides being somehow constrained by the final product life-cycle whose components the firm is interested to produce.

Next sections describe three different business strategies and the related production problems the manufacturing strategy should face.

5.4 Business Strategy: Focalization

This section describes the case of a company that, for instance, is a first-tier supplier of an Original Equipment Manufacturer (OEM). The company aims at pursuing a focalization strategy on the OEM final product and producing one or more components related to it. In this case, the company will determine its production problem based on the scenario tree for the OEM final product. Then, the components to be produced will be either parts of the same final product or parts of different products. If components are all parts of the same final product, the work-piece scenario tree structure corresponds to the final product one while the part mix volumes for each node are given by the Bill of Material (BoM) quantity for each component. On the other hand, if the

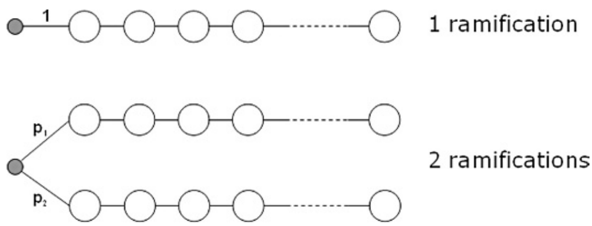


Fig. 5.9 Scenario tree with one or two ramifications

components are part of different final products, the scenario tree results from the composition of the specific scenario trees for each final product and therefore it will be determined by taking into account the combinations of demand configurations.

However, if only two final products are considered, only three possible scenario tree structures can occur. Indeed, if the components are child of the same final product, the scenario tree is easily obtained and only two structures can be identified as reported in Fig. 5.9. One ramification occurs when, for instance, the final product has a long life-cycle and its initial state is “decline“ or when it has a short life-cycle; two ramifications occur when, for instance, the final product has a long life-cycle and its initial state is “maturity”. On the other side, when the components are part of two different final products, the workpiece scenario tree is composed at most of four ramifications, as showed in Fig. 5.10. This last case can occur when considering the composition of two life-cycle ramifications per final product (that would be when, for instance, both products have a long life-cycle and both initial states are “growth”).

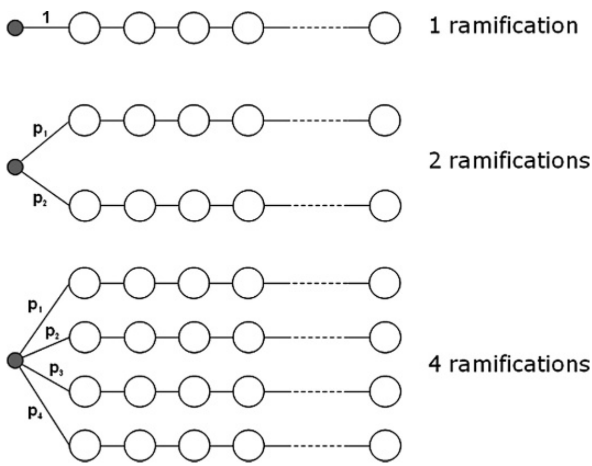


Fig. 5.10 Scenario tree with one or two or four ramifications

5.4.1 Focalization: Examples

Case 1 – Consider the case of two components *a* and *b*:

- *a* is a component of the final product *A*, with a long life-cycle and initial phase of decline;
- *b* is a component of the final product *B*, with a short life-cycle.

In this case, for component *a* only the branch related to the long life-cycle has to be considered, whereas for component *b* only the ramification related to the short life-cycle has to be taken into account. Therefore the scenario tree resulting from the composition is shown in Fig. 5.11:

Case 2 – Consider the case of two components *a* and *b*, both parts of the same final product *A* with a long life-cycle and initial phase of maturity. From Fig. 5.8, it comes out that the combination scenario tree is the one depicted in Fig. 5.12:

Case 3 – Consider the case of two components *a* and *b*:

- *a* is a component of the final product *A*, with a long life-cycle and initial phase of growth;
- *b* is a component of the final product *B*, with a medium life-cycle and initial phase of decline.

In this case, for the component *a* the branch related to the long life-cycle has to be considered, while for *b* the ramification related to the medium life-cycle need to be taken into consideration.

The scenario tree resulting from the combination of two different configurations of the life-cycles of different final products is reported in Fig. 5.13:

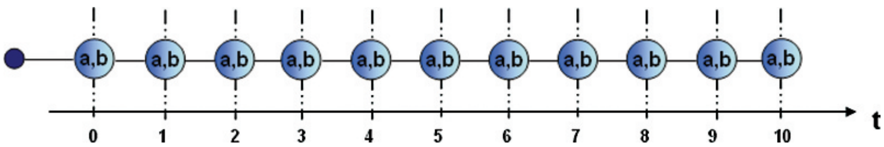


Fig. 5.11 Scenario tree: components (*a* and *b*) of different final products

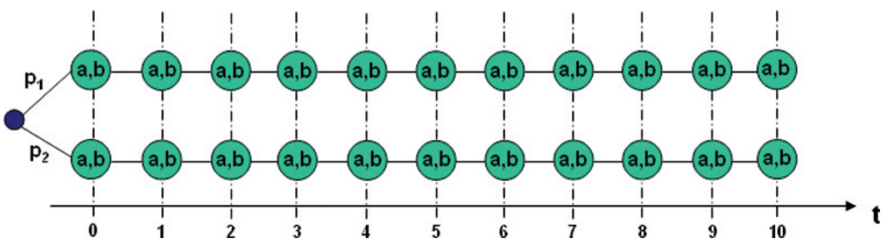


Fig. 5.12 Scenario tree: components (*a* and *b*) of the same final product

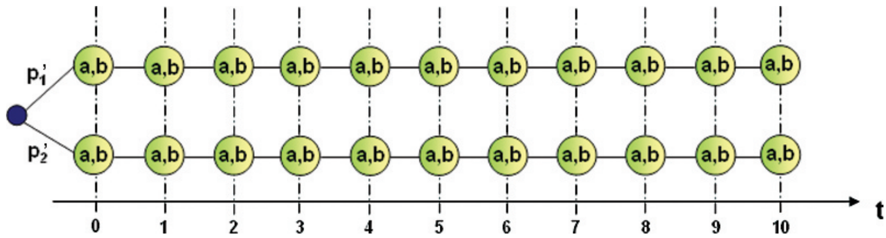


Fig. 5.13 Scenario tree: components (*a* and *b*) of the different final product

Case 4 – Consider the case of two components *a* and *b*:

- *a* is a component of the final product *A*, with a long life-cycle and initial phase of maturity;
- *b* is a component of the final product *B*, with a medium life-cycle and initial phase of growth.

In this case, the scenario tree results from the composition of two different configuration of life-cycle for the different final products *A* and *B*. As represented in Fig. 5.14, the final scenario tree structure is made of four ramifications

5.5 Business Strategy: Differentiation

This section illustrates the case in which the firm stays in the same market and tends to differentiate its product by introducing a new component *c* (of the same kind of *b* sub-component of *B*), which is a component of the final product *A*. In this case the scenario tree of the single component *c* is very similar to the one already discussed for *a* or *b*. The only difference consists in defining two new demand parameters connected to the moment by which the new component will be introduced. In fact, it could be introduced at time $t_0 = 0$ (immediate entrance

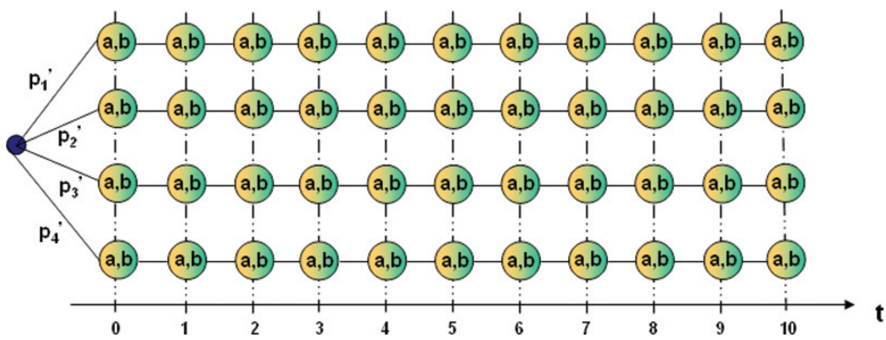


Fig. 5.14 Scenario tree: components (*a* and *b*) of the different final product

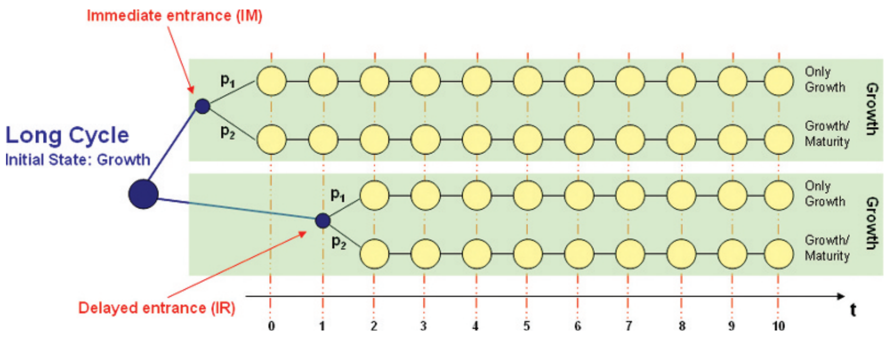


Fig. 5.15 Configuration tree: immediate entrance and delayed entrance

IM) or at a following time $t_1 > t_0$ (delayed entrance *IR*). An example of this new situation is reported in Fig. 5.15 and regards the case of long life-cycle and initial phase of growth.

Considering the product life-cycle shape (Fig. 5.3) which has been defined according to parameters *IS*, *IE*, *DS*, *DE*, and *V*, it is necessary to define others two parameters that regard the introduction of the new component, respectively Fast Increase Start (*FIS*) and Fast Increase End (*FIE*). Figure 5.16 shows the two cases. In particular, the first case (on the left) refers to the immediate entrance of a new component while the second case (on the right) refers to the delayed entrance, and both are compared with the final product life-cycle which is described by a dashed blue line.

The Fast Increase Start (*FIS*) represents the point when the new component is introduced (i.e. when its growth starts). In the case of immediate entrance (*IM*), at time $t_0 = 0$, the *FIS* coincides with the *IS* (Increase Start), while in the case of delayed entrance (*IR*) the *FSI* will be obviously delayed with respect to the *IS*.

The Fast Increase End (*FIE*), instead, represents the point when the phase of growth ends and the phase of maturity begins. Therefore, the new component

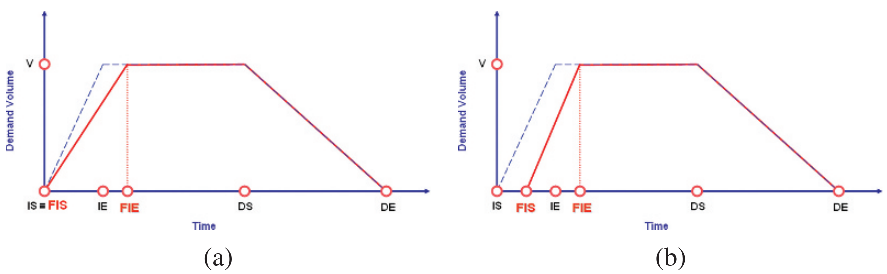


Fig. 5.16 New component life-cycle: Immediate entrance (**a**) and Delayed entrance (**b**)

life-cycle is given from the final product life-cycle and differs for the two parameters (*FIS* and *FIE*).

Besides defining such new demand parameters, the possible scenario tree structures to be considered in the case of “differentiation” business strategy are identical to those of “focalization” strategy. Indeed, even if, for example, three different components (*a*, *b* and *c*) are taken into account, the scenario tree structure will present, as before, four ramifications at most as the main assumption is that the new (differentiated) component “*c*” is of the same type of the one of the components which have already been considered “*a*” and it is part of a final product “B” whose sub-components (at least one – “*b*”) has already been considered.

5.5.1 Differentiation: Example

Consider the case of two components *a* and c:

- *a* is a component of the final product *A*, with a long life-cycle and initial phase of growth;
- *c* is a new component of the same final product *A*.

Both components are members of the same final product and the introduction of the new component has to be hypothesized. In this case a delayed entrance has been assumed and in particular the new component is introduced at time stage $t = 3$, as shown in Fig. 5.17.

5.6 Business Strategy: Diversification

This section deals with the case in which the firm wants to diversify the production by producing a new component *d* (of the same kind as b), but part of the final product *C*. As in the differentiation strategy, the new component can be introduced immediately (Immediate Entrance) or later (Delayed Entrance) as well.

Also in this case the scenario tree results from the composition of the configuration trees for all the components. However, differently from the case

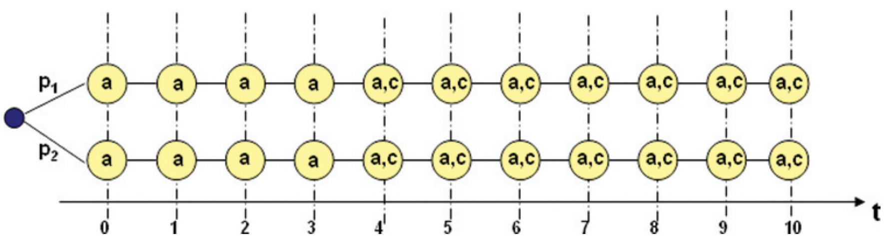


Fig. 5.17 Scenario tree: the introduction of a new component *c*

of “differentiation” strategy, in the situation of three components (*a*, *b*, *d*), the scenario tree structure will present eight ramifications at most since the main assumption is: the new component “d” is of the same type of part “b”, which has already been considered; however, “*d*” belongs to a different final product, i.e. “*C*”, whose sub-components have not already been considered. For these reasons, the three components could be parts of three different final products.

5.6.1 Diversification: Example

Consider the case of three components *a*, *b* and *d*:

- *a* is a component of the final product *A*, with a long life-cycle and initial phase of growth;
- *b* is a component of the final product *B*, with a medium life-cycle and initial phase of growth.
- *d* is a component of the final product *C*, with a medium life-cycle and initial phase of maturity;

In this case, there are three components of three different products and the scenario tree results from the composition of different product life-cycle. Therefore there will be eight ramifications, as shown by Fig. 5.18.

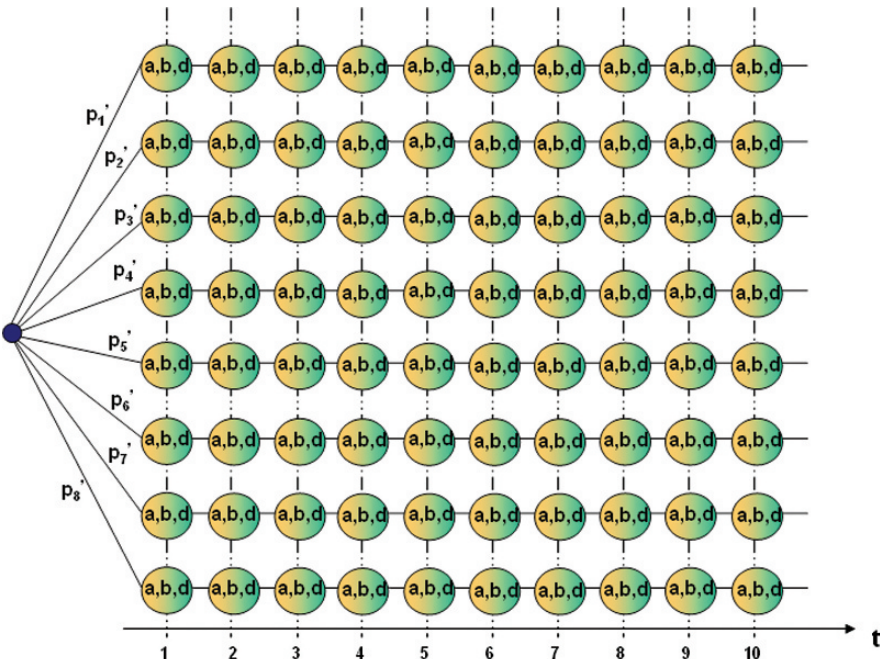


Fig. 5.18 Scenario tree: components (*a*, *b* and *c*) of the different final products

5.7 A Tool for Production Problem Generation

This section introduces a decision support system (DSS) that has been developed for generating the production problem scenario tree starting from some information about final products, components and company business strategy. The DSS is a concrete tool for operationalizing the manufacturing strategy and is based on the scenario tree generation models that have been discussed so far. The DSS has been developed in Visual Basic programming language and integrated with a Microsoft Access Database sending out some input parameters in order to generate the scenario tree and receiving output results, i.e. the scenario tree which has been generated.

The DSS is based on a windows-based interface which supports the planner throughout the whole manufacturing strategy operationalization process. Depending on the chosen business strategy (Fig. 5.19), the DSS leads the planner to define final products and component life-cycles in terms of demand parameters together with probability values associated with final product demand evolution uncertainties (Fig. 5.20).

Once the user has inserted information about given strategy, final product demand profiles, bill of material of each products and work-pieces to be produced, the DSS determines the proper scenario tree structure related to the given problem and calculate all of the data settling on the nodes of the scenario tree. Specifically Fig. 5.21 shows a scenario tree structure represented as Microsoft Access tables (Table 4.21). By detail:

- the table Scenario Node stores data about the scenario tree structure (one, two, four or eight ramifications);

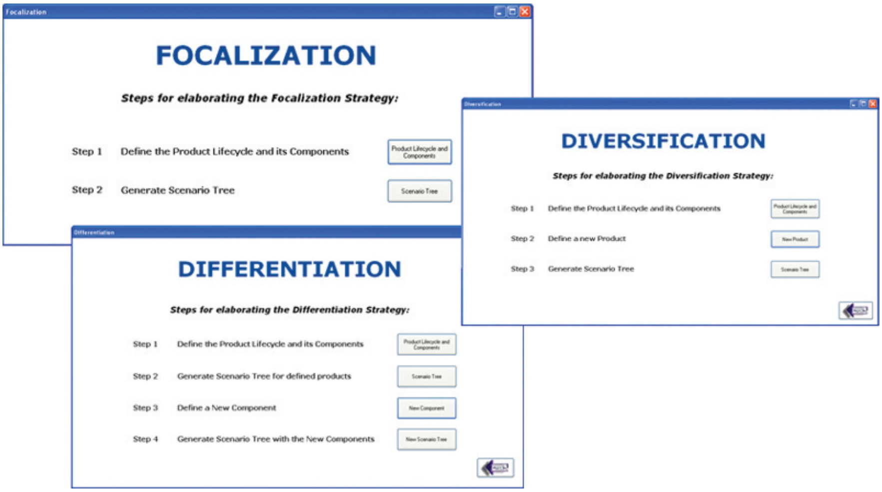


Fig. 5.19 DSS forms for generating the scenario tree

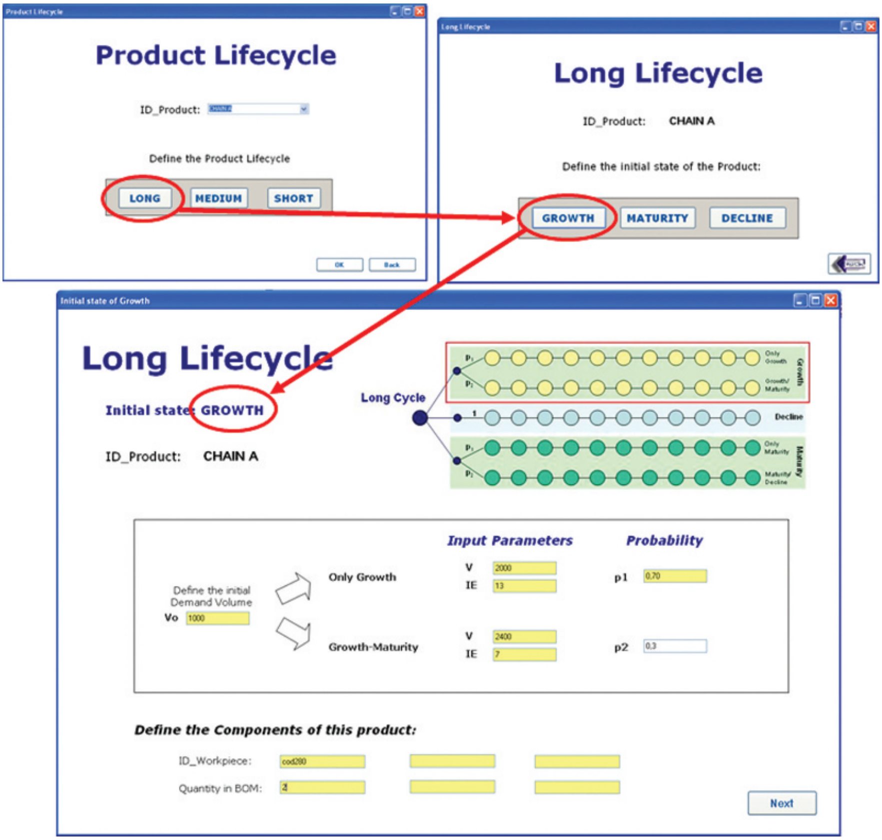


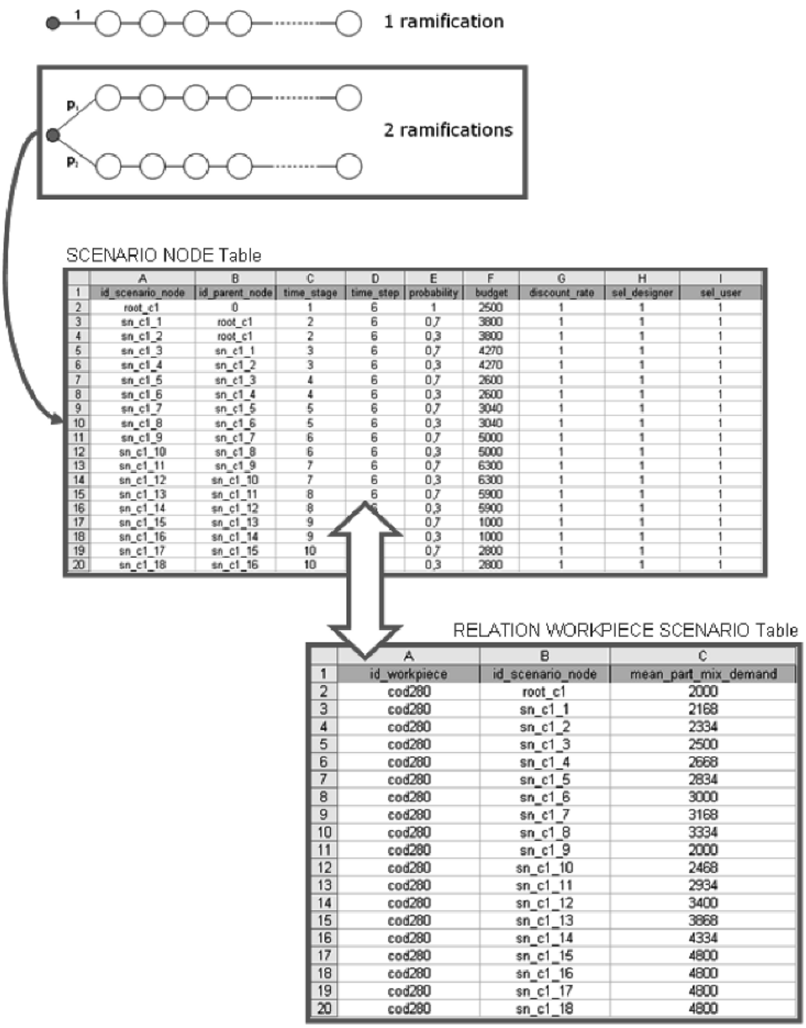
Fig. 5.20 DSS forms for supporting the inputting of data on product and component life-cycles

- the table Relation Workpiece Scenario stores data about each node product mix demand.

5.8 Numerical Example

The numerical example consists of comparing two similar production problems. Both problems are characterized by data reported in Table 5.1.

The two production problems only differ for the business strategy parameter *FIS* which is equal to 0 in Case 1 (i.e. immediate entrance) and is equal to 3 in Case 2 (i.e. delayed entrance). Both the production problems bring to the same scenario tree structure, which is made of 4 scenarios with occurrence probability equal to $p^B{}_1 \times p^C{}_1$, $p^B{}_2 \times p^C{}_1$, $p^B{}_1 \times p^C{}_2$, and $p^B{}_2 \times p^C{}_2$, respectively. However,



SCENARIO NODE Table

	A	B	C	D	E	F	G	H	I
1	id_scenario_node	id_parent_node	time_stage	time_step	probability	budget	discount_rate	sel_designer	sel_user
2	root_c1	0	1	6	1	2500	1	1	1
3	sn_c1_1	root_c1	2	6	0,7	3800	1	1	1
4	sn_c1_2	root_c1	2	6	0,3	3800	1	1	1
5	sn_c1_3	sn_c1_1	3	6	0,7	4270	1	1	1
6	sn_c1_4	sn_c1_2	3	6	0,3	4270	1	1	1
7	sn_c1_5	sn_c1_3	4	6	0,7	2600	1	1	1
8	sn_c1_6	sn_c1_4	4	6	0,3	2600	1	1	1
9	sn_c1_7	sn_c1_5	5	6	0,7	3040	1	1	1
10	sn_c1_8	sn_c1_6	5	6	0,3	3040	1	1	1
11	sn_c1_9	sn_c1_7	6	6	0,7	5000	1	1	1
12	sn_c1_10	sn_c1_8	6	6	0,3	5000	1	1	1
13	sn_c1_11	sn_c1_9	7	6	0,7	6300	1	1	1
14	sn_c1_12	sn_c1_10	7	6	0,3	6300	1	1	1
15	sn_c1_13	sn_c1_11	8	6	0,7	5900	1	1	1
16	sn_c1_14	sn_c1_12	8	[illegible]	0,3	5900	1	1	1
17	sn_c1_15	sn_c1_13	9	[illegible]	0,7	1000	1	1	1
18	sn_c1_16	sn_c1_14	9	[illegible]	0,3	1000	1	1	1
19	sn_c1_17	sn_c1_15	10	[illegible]	0,7	2800	1	1	1
20	sn_c1_18	sn_c1_16	10	[illegible]	0,3	2800	1	1	1

RELATION WORKPIECE SCENARIO Table

	A	B	C
1	id_workpiece	id_scenario_node	mean_part_mix_demand
2	cod280	root_c1	2000
3	cod280	sn_c1_1	2168
4	cod280	sn_c1_2	2334
5	cod280	sn_c1_3	2500
6	cod280	sn_c1_4	2668
7	cod280	sn_c1_5	2834
8	cod280	sn_c1_6	3000
9	cod280	sn_c1_7	3168
10	cod280	sn_c1_8	3334
11	cod280	sn_c1_9	2000
12	cod280	sn_c1_10	2468
13	cod280	sn_c1_11	2934
14	cod280	sn_c1_12	3400
15	cod280	sn_c1_13	3868
16	cod280	sn_c1_14	4334
17	cod280	sn_c1_15	4800
18	cod280	sn_c1_16	4800
19	cod280	sn_c1_17	4800
20	cod280	sn_c1_18	4800

Fig. 5.21 A 2-ramification scenario three represented in a Microsoft access table

because of the different FIS values the variability of part mix and volumes in the Case 2 scenario tree is higher. Indeed, in each scenario, starting from time stage *FIS*, the three components of final product *B* have to be produced and this, for obvious reasons, increases the variability of scenario nodes volumes and mix.

Table 5.2 reports the results of this numerical example in terms of average and standard deviation of volumes of cod380.

The numerical example shows a simple application of the operationalization approach that has been proposed in this chapter. Indeed, the example compares two similar production problems that, however, require different levels of

Table 5.1 Numerical example information

Settings	Final product A	Final product B	Final product C
Life-cycle length	SHORT	LONG	LONG
Initial stage	GROWTH	GROWTH	GROWTH
Demand configuration parameters	V0 = 2000; V = 4000; IE = 2; DS = 4; DE = 6;	V0 = 3000; $p^B{}_1$ = 0.3 (V = 6000; IE = 13); $p^B{}_2$ = 0.7 (V = 5400; IE = 5)	V0 = 4000; $p^C{}_1$ = 0.7 (V = 7000; IE = 12); $p^C{}_2$ = 0.3 (V = 5700; IE = 7)
Component codes	cod240 (QBOM = 1), cod268 (QBOM = 1), cod270 (QBOM = 1)	cod280 (QBOM = 1)	cod380 (Q_{BOM} = 2), cod525 (Q_{BOM} = 1), cod916 (Q_{BOM} = 2)
Business strategy	Focalization	Focalization	Diversification

Table 5.2 Results from the numerical example

Case	FIS	Scenario	Occurrence probability	cod380 volumes Average	cod380 volumes Standard deviation
1	3	1	0.21	7891.6	5530.0
		2	0.49	7891.6	5530.0
		3	0.09	7440.2	5253.3
		4	0.21	7440.2	5253.3
2	0	1	0.21	8855.6	4287.1
		2	0.49	8855.6	4287.1
		3	0.09	8210.4	4226.7
		4	0.21	8210.4	4226.7

flexibility (part mix and volumes are much more variable in Case 2, as proved by the higher level of cod380 volume standard deviation σ along the time horizon T). Such considerations are, hence, very important for the manufacturing system design phase and for establishing whether a FFMS solution is suitable for a given production problem or not.

5.9 Conclusions

Twenty-five years later his seminal papers on manufacturing strategy, Wickham Skinner (1996) tried to explain in some ways why manufacturing strategy concepts (such as strategic fit, focused factory, trade-offs, plants-within-the plant, etc.) are as much flourishing and rapidly growing in popularity in academic literature as modestly, if not scarcely, used in the real industrial management practice. From that analysis the author recognized that, among the others, probably the main reason for that is imputable to the fact that "…we ask manufacturers to explicitly describe a manufacturing task and then design all the structural elements to set up an internally coherent system to fit the task. But how is this to be done?" (Skinner 1996). Basically, what is still missing is a set of tools and methods that help managers to "engineer" manufacturing strategies. The research presented in this chapter aims at giving a contribution along this direction, by proposing an operationalization framework that should support managers in translating manufacturing strategy decisions into specific manufacturing system design specifications.

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Chapter 6
Pallet Configuration for Approaching Mapping Requirements on Devices

Giovanni Celano, Antonio Costa, Sergio Fichera and Barbaro Santangelo

Abstract The correct configuration of a system is a strategic problem whenever a tool manufacturer should select the optimal solution to tackle a specific production problem. Once information concerning the production problem has been provided to the machine tool builder, it is possible to start the technological analysis of the part family which represents a very critical phase of the system design process. In particular, process plans to produce the workpieces need to be defined. To reach this goal it is necessary to elaborate a mapping between the part types to be produced and the available manufacturing resources. To this purpose, each machining feature of the various part types is matched with an operation or a sequence of operations, taking into consideration the feasible setups. This chapter provides a procedure named Mapping Requirement on Devices generating different process plans. It is based on three main modules. The first module performs a setup planning procedure; the second module deals with the problem of pallet configuration, whereas the last module performs the sequencing of the part setups and generates a set of alternative process plans. These process plans will then be taken into account in the selection of system resources. The results obtained in the testing phase address the importance of developing a procedure based on multi-setup fixtures instead of considering a single setup per pallet.

Keywords Process planning · Setup planning · Pallet configuration · Setup sequencing

6.1 Introduction

The system configuration approach proposed in this book defines the characteristics of manufacturing systems designed to achieve the optimal trade-off between productivity and flexibility. To this aim, the number and type of

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resources which are able to properly satisfy a given production problem need to be selected. Usually, a machine tool builder invests a considerable amount of time and money in the design of a production system. However, the final solution is usually obtained on the basis of its experience and few tools focused on specific tasks support the design process. During this activity it is possible to compare different process options and to evaluate their benefits. In particular, the system designer can provide a wide set of alternative machine configurations starting from the analysis of alternative process plans. The identification of the setups required to produce a part is one of the key issues that characterizes the process planning problem. Indeed, a proper "setup planning" phase assumes a central role in the evaluation and selection of the best configuration of a machining center.

In this work it is assumed that parts to be machined are mounted on a pallet (i.e. a physical device consisting of various components: table, fixture, etc.). This assumption is quite general and applicable to many industrial cases. One consequence of this assumption is that, in addition to the machining centers, the pallets also need to be properly configured.

The aim of this chapter is to address the setup planning and pallet configuration problem, in order to support the system designer during his activities. Indeed, at the end of the setup planning and pallet configuration procedure, a set of alternative process plans and their corresponding pallet configurations are generated. These elements represent an important input for the system configuration phase.

This chapter is organized as follows. A brief literature overview is reported in Sect. 6.2; the problem statement and the proposed procedure are presented in Sect. 6.3. Sect. 6.4 discusses the setup planning procedure which consists of three steps:

1. workpiece setup generation;
2. setup face configuration;
3. tool path and rapid movements.

The pallet configuration algorithm is explained in Sect. 6.5. The setup sequencing procedure which generates the different process alternatives is described in Sect. 6.6. Finally some conclusions have been drawn based on the overall methodology and on its theoretical implications.

6.2 Literature Background

In the past decades, the setup planning issue has had a wide impact on the literature concerning Computer Aided Process Planning (CAPP) applications. Usually, setup planning has been considered as a tool supporting companies to cope with the increased product diversification (Wang and Luh 1996). In this study, however, the setup planning activity is seen as a strategic step of a wider procedure, aimed at supporting manufacturing system design. Given these statements it is possible to define two different roles for the setup planning activity: an operating role, as an integral part of CAPP systems, which deals with the optimization of the shop-floor operations, and a strategic role which supports the system designer in the system configuration activity.

An important investigation on the strategic role of setup planning for machining centers configuration has been provided by Contini and Tolio (2004). They proposed a method to define near-optimal setup plans for prismatic workpieces, when multiple parts can be mounted on the same pallet. Setups are determined taking into account the accessibility of the machining directions of the workpiece and the technological constraints among the required operations. Starting from the results of setup planning the authors also considered the pallet configuration issue as a key factor for an optimal configuration of machining centers.

With reference to the operating role of setup planning, many authors dealt with this aspect by investigating the properties and performances of CAPP systems.

One notable approach on automated setup planning in CAPP applications was performed by Zhang and Lin (1999), who utilized the basic concepts of hybrid graphs. They stated that setup planning in CAPP consists of recognizing machining features and extracting initial information, grouping to-be-machined features into setups, sequencing the setups, and selecting setup datums. The theoretically exact point, axis, or plane used to locate the part is referred to as a setup datum. The authors considered the tolerance analysis as a critical step of setup planning. In their algorithms all the parts are assumed to be machined on 3-axis vertical milling centers.

More recently, Yao et al. (2007a,b) introduced a comprehensive system for the process planning of non-rotational parts. In their approach, setup planning plays a key role together with manufacturing resource analysis and fixture design. Since flexible manufacturing resources are used in mass customization, manufacturing planning must be designed to cope with these types of flexible resources. Thus, as stated by the authors, both manufacturing resource capability analysis (manufacturing resources include machine tools, cutting tools and fixtures) and setup planning (whose goal is to determine the number of required setups, the orientation of the workpiece and the process plan for each setup) represent the foundations of such manufacturing planning.

Cai et al. (2008) proposed an adaptive setup planning approach which is applicable to various configurations of machine tools. Optimal setup plans are selected according to multiple optimization criteria. Starting from a 3-axis based machining feature grouping, all the setup plans of a given part are defined by examining the tool accessibility for different types of machine tools.

Hebbal and Mehta (2007) focused their paper on the development of a formalized procedure for the automatic generation of feasible setups and the selection of the optimal setup plan for a prismatic part. They proposed a technique which simultaneously considers the basic concepts of setup planning from both machining and fixture viewpoints in order to formulate feasible setup plans.

A similar optimization-based approach was suggested by Zhang and Peng (2005) who developed an approach for setup planning where setups are automatically planned, based on some key factors derived from machining practice: tolerance requirements, manufacturing costs and fixture constraints coming from fixture design. Setup planning and fixture planning are considered two closely related tasks of process planning which affect the overall cost and quality of the part to be machined. The integrated approach developed by the authors enables the user to simultaneously address setup planning and fixture design.

Although most of the reported approaches efficiently address the setup planning issue for stand alone machines, it is apparent that the need for communication between a setup planning system and other planning and designing tools such as CAPP and Computer Aided Fixture Design (CAFD) has to be fulfilled. In this context, in order to emphasize the key role of information sharing within a planning and designing environment, an innovative approach based on Java and Web technologies, called “internet-based setup planning”, has been proposed to handle the setup planning issue (Peng et al. 2005; Liu and Peng 2005).

6.3 The Process Configuration Issue

6.3.1 Problem Statement

In accordance to the information formalization framework presented in Chap. 4, three main areas are involved in the decisional process when several process plans are taken into account to manufacture a product: the “Product”, the “Process” and the “Production System” areas. For each area several classes have been defined, partially according to the STEP-NC standard (ISO/DIS 14649). The following classes define the input information needed to address the process configuration problem. Herein, the attributes related to each class have been omitted, while a comprehensive description is provided by Chap. 4:

- Product area
  - *Workpiece*. This is the part to be produced within the system. It includes information concerning the geometrical dimensions of the part.
  - *Machining Feature*. This is the entity defining the workpiece technological requirements. Examples of machining features are: planar face, pocket, slot, step, hole, etc. The position and orientation of each feature within the workpiece coordinate system are defined through a set of linear coordinates and a direction cosine matrix respectively.
- Production System area
  - *Machine*. This represents the machining centers available in the actual manufacturing system or in the machine manufacturer catalogue. The

main attributes involved in this study are: working cube dimensions, rapid traverse speed for each axis, number of controlled axes, machine power and pallet table size.
  - *Physical Pallet*. This is a physical element consisting of the combination of a table and a fixture with one or more faces (i.e. the fixture faces) which can be used to load the workpieces. The fixture dimension is the primary attribute to be considered for determining the number of pieces that can be loaded on the pallet.

- Process area
  - *Machining Operation*. Each feature needs a machining operation to be processed: the machining tool and a set of technological parameters are required to define a machining operation.
  - *Machining Workingstep*. The association of a machining feature and a machining operation defines a machining workingstep. Thus, it represents a specific operation that a machine can make on a particular feature. Moreover, precedence and tolerance constraints among workingsteps are here characterized. Tolerance constraints are expressed in terms of machining workingsteps that must be processed with the same pallet and on the same machine.

The process planning issue involves a setup planning activity which consists of defining the setups necessary to machine all the workingsteps required by a workpiece, with reference to the available system resources. Each machining workingstep is characterized by information on its working direction; thus, each setup needed by a workpiece can be associated with a group of machining workingsteps and also to a set of working directions. Whenever a workpiece is clamped on a fixture and then loaded onto a machining center, the manufacturing of each workingstep depends on the machine degree of freedom and, at the same time, on the specific setup selected for the workpiece. In fact, the main requirement to process a workingstep consists of the lining up between the workingstep working direction and the tool axis. Moreover, since several workpieces could be clamped onto the same fixture, some workingsteps could be inaccessible by the tool. As a consequence, given the workpiece clamping configuration on the pallet, the setup planning issue requires an efficient inverse kinematics analysis to verify whether each working direction is accessible by the machining tool, in order to select a set of distinct setups which allows the machining of all the workingsteps.

Usually, a workpiece needs more than one setup to be processed and a pallet has more than one fixture face wherein workpieces can be loaded according to their planned setups. The pallet configuration problem consists of the generation of one or more alternative pallet configurations by matching the setups required by a workpiece with the different fixture faces available on a pallet. The amount of solutions that may arise from a pallet configuration procedure depends on the number of setups required by a workpiece and on the set of available pallet types. For instance, for a given part which needs four setups and for a physical pallet equipped with four fixture faces, it is possible to configure a maximum of four distinct pallets and a minimum of one pallet to process the workpiece. The former case means that all the fixture faces of a single pallet are arranged in the same manner, i.e. all the workpieces that fill up the fixture faces are clamped on with the same setup. The latter case means that each fixture face holds a different setup.

Generally, machining workingsteps are linked to each other by precedence relations that arise from tolerance and technological constraints. The problem of defining the proper sequence of machining workingsteps becomes particularly important when a workpiece requires different setups to be machined. This means that a pallet can hold workpieces which are mounted according to just one setup or according to more than one setup. In both cases, a pallet must be processed respecting a precise sequence which strictly depends on the constraints among the workingsteps. Each sequence of pallets may be defined as an alternative "workplan of pallets" which entails integration between the setup planning and the pallet configuration activity.

6.3.2 Outline of the Proposed Procedure

With reference to the aforementioned problem statement, the proposed approach, named Mapping Requirements on Devices (MRD), has been developed on the basis of the following main hypotheses:

- Only prismatic parts have been considered as a workpiece to be processed.
- Workpieces can be processed by four- and five-axis horizontal CNC machines.
- All the operations required to machine a feature have to be performed in the same setup.
- Only workpieces of the same type can be mounted on a pallet, i.e. no pallets holding different part types are allowed.
- Each fixture face belonging to a pallet is configured with parts having the same setup.
- All the available fixture faces of a pallet are occupied by parts to be machined.
- The same setup is associated with opposite fixture faces in pallets with more than one fixture face, according to a symmetrical configuration.
- Whenever a part requires four setups, a pallet with four fixture faces can be configured with parts having a different setup in every face.

Figure 6.1 describes the structure of the MRD procedure which aims to address the process planning and pallet configuration problems. This procedure consists of three modules:

1. Setup Planning;
2. Pallet Configuration;
3. Setup Sequencing.

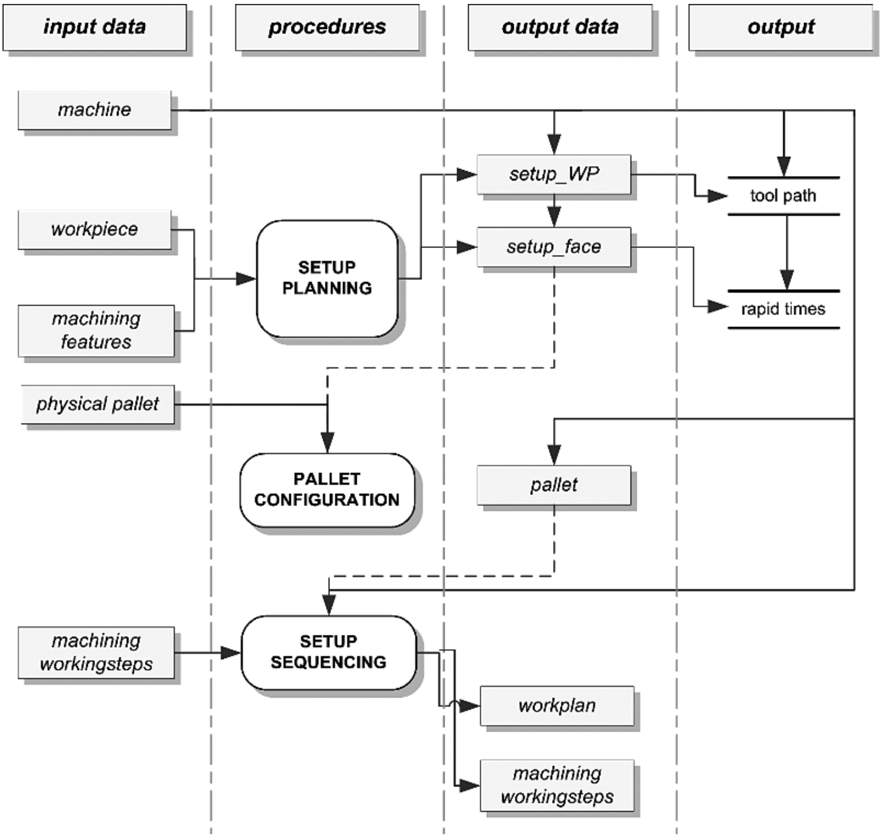

Fig. 6.1 The mapping requirement on devices procedure

The Setup Planning module is composed of three sub-modules. The first sub-module, named "workpiece setup generation", generates the whole set of potential setups. The potential setups are defined starting from an initial clustering of machining workingsteps based on a three degree of freedoms machine configuration. Then, on the basis of the fixture dimension wherein the workpiece has been clamped, the second sub-module "setup face configuration" takes into account a four axis CNC machine and groups the machining workingsteps aiming at maximizing the number of workpieces clamped on the same fixture face. Afterwards, a single fixture face (associated with a given physical pallet) whereon a set of workpieces are mounted with the same setup is called "setup face". Due to the loading of more than one workpiece on each setup face, the setup face configuration problem takes into account the tool accessibility constraint by adopting a fixed tolerance distance between adjacent workpieces.

For each configured setup face, the last sub-module “tool path generation” determines the tool path related to each machining workingstep taking into account the kinematic parameters of the considered machines when computing tool rapid feed rate times.

The second module running within the MRD procedure is the “Pallet Configuration” module. It exploits the setup face configuration data determined by the previous module. Then, by matching this information with the available physical pallet data, it generates alternative pallets as a combination of several setup faces. As reported in the previous sub-section, the number of pallets that can be configured depends on the number of setups required by a given workpiece and on the physical pallet geometry expressed in terms of available fixture faces.

The “Setup Sequencing” module completes the MRD procedure and combines pallet, workingstep and machine information to generate alternative workplans. Precedence constraints among workingsteps can involve workingsteps which have been assigned to the same pallet or to different pallets. The satisfaction of the precedence relations among workingsteps assigned to the same pallet is taken into account during the part program generation, while the Setup Sequencing module must generate alternative workplans (i.e. sequences of pallets) satisfying the precedence relations among workingsteps assigned to different pallets.

All the modules composing the Mapping Requirements on Devices (MRD) procedure will be further detailed in the following sections.

6.4 Setup Planning

In recent decades, computer numerical control (CNC) machines have improved their performances thanks to some auxiliary components such as four- and five-axis rotary tables. The proposed Setup Planning procedure manages three distinct problems for a given workpiece: the setup generation in relation to specific machines and physical pallets, the setup face configuration associated with each setup and the tool path and rapid feed rate time computation associated with each setup face. All of these problems will be addressed in the following sub-sections.

6.4.1 Workpiece Setup Generation

According to the diagram reported in Fig. 6.1, the “Setup Planning” receives the geometrical and feature based workpiece data as input. Starting from a specific workpiece, a proper algorithm reads the working directions for each feature on the basis of its direction cosine matrix provided by the attributes of the “machining feature” class. The direction cosines describe the feature working direction, i.e. the so-called Tool Approach Directions (TADs), with respect to an assigned workpiece linear coordinate system. Given a workpiece, a distinct placement is defined for each face of its envelope cube. Independently of the assigned features, the proposed Setup Planning procedure considers up to six different workpiece placements for a prismatic part. Whenever the unit vector of a face, defined with respect to the workpiece coordinate system, is aligned with the tool z-axis, then a so-called "standard placement" is individuated. The unit vector associated with each face of the workpiece envelope cube (e.g. see Fig. 6.2) identifies a Standard Placement Direction (SPD). As a consequence, each feature (or group of features having the same working directions) must be assigned to one of the six standard placements. Furthermore, machining features whose working directions are rotated with respect to the workpiece linear coordinate system are initially allocated to properly generated dummy placements. This is a common approach in setup planning literature where three degree of freedom machines are used to define the potential setups for a given workpiece (Zhang and Lin 1999). Since in this study a setup is defined as a specific workpiece standard placement combined with a specific workpiece orientation on a fixture face, different potential setups can be considered. In particular, 12 potential setups have been determined by taking into account a four degree of freedom machine which allows removing each rotated feature from its dummy placement and associates such feature to a properly selected potential setup. In fact, a four-axis machine can machine a rotated feature by taking advantage of its rotary table. Among those potential setups, only a minimum number of setups, named "ultimate setups", must be selected in relation to well-defined heuristic rules reported below. In order to explain how the Setup Planning procedure works, Fig. 6.3 presents two views of a sample workpiece characterized by five machining features: feature f_1 is an

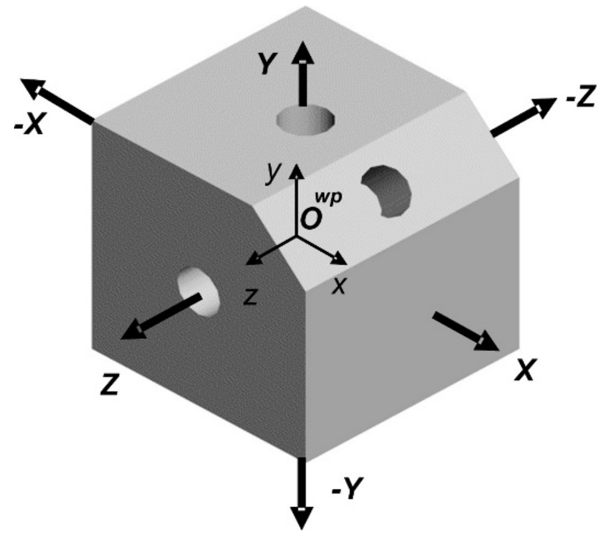

Fig. 6.2 Standard placements directions for a sample workpiece

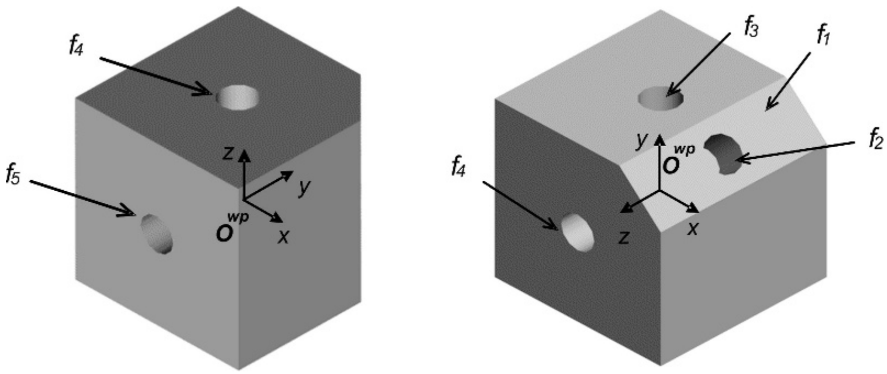

Fig. 6.3 Two views of the sample workpiece

oblique planar face, while features from f_2 to f_5 are blind holes. Feature f_5 is symmetrical to feature f_3, and it can be machined when the –Y standard placement direction is aligned with the tool z-axis. Moreover, each feature, properly associated with its required machining operation, determines a machining workingstep (e.g. WS_1, WS_2, WS_3, WS_4, WS_5) In this study only horizontal machining centers have been taken into account; the machine coordinate system (O^m) whose z-axis coincides with the spindle direction is reported in Fig. 6.4. Considering the orientation of the direction cosines of the workpiece linear coordinate systems (O^{wp}) with respect to the machine linear coordinate system (O^m), the standard placements of the workpiece can be defined as follows:

- $\cos(zx) = +1$, the machine spindle z-axis has the same direction and orientation of the workpiece x-axis;
- $\cos(zx) = -1$, the machine spindle z-axis has the same direction and opposite orientation with respect to the workpiece x-axis;

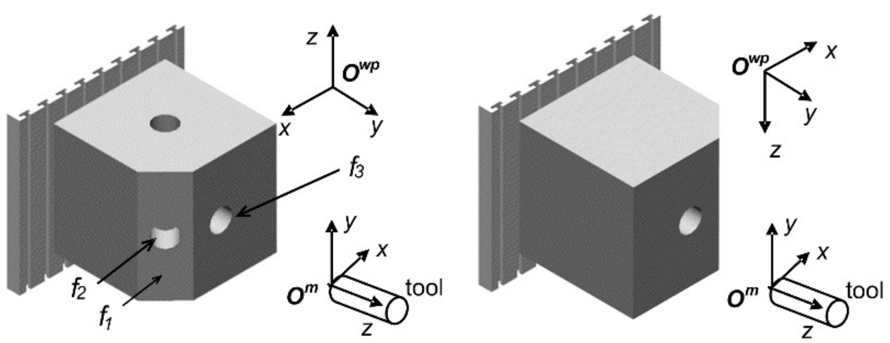

Fig. 6.4 Sample workpiece setup (i) and setup (iii)

- $\cos(zy) = +1$, the machine spindle z-axis has the same direction and orientation of workpiece y-axis;
- $\cos(zy) = -1$, the machine spindle z-axis has the same direction and opposite orientation with respect to the workpiece y-axis;
- $\cos(zz) = +1$, the machine spindle z-axis has the same direction and orientation of the workpiece z-axis;
- $\cos(zz) = -1$, the machine spindle z-axis has the same direction and opposite orientation with respect to the workpiece z-axis.

Two possible setups arise from each standard placement, each one associated with a different workpiece orientation. Actually, four different orientations of the workpiece may be associated with a standard placement but only two of them can be considered as necessary to the setup planning activity. For instance, the four potential setups in the following list are defined as the combination of a standard placement and four distinct orientations:

i. $\cos(zy) = +1$; $\cos(yz) = +1$; $\cos(xx) = -1$;
ii. $\cos(zy) = +1$; $\cos(yx) = +1$; $\cos(xz) = +1$;
iii. $\cos(zy) = +1$; $\cos(yz) = -1$; $\cos(xx) = +1$;
iv. $\cos(zy) = +1$; $\cos(yx) = -1$; $\cos(xz) = -1$;

As shown in Fig. 6.4, setup (i) and setup (iii) should be considered equivalent since features f_1, f_2, f_3 can be likewise accessed by a four-axis machining center. As a consequence, setups (iii) and (iv) should be considered homologue to setups (i) and (ii), respectively; thus, only a couple of them should be taken into account to address the setup planning task.

The total number of non-homologue possible setups for the prismatic part is equal to 12. Since it is assumed that all the workpieces clamped on a setup face have the same setup, both potential setups (i) and (iii), and potential setups (ii) and (iv) can be considered equivalent to each other.

All the feature working directions (z-feature) of the sample part, computed with respect to the workpiece linear coordinate system, are reported in Table 6.1: *Feature* represents the feature code, *Feature type* is the type of feature according to ISO14649-10 and the direction cosines are related to the angle between the workpiece coordinate system (x^{wp}, y^{wp}, z^{wp}) and each feature z-axis.

Working on the basis of 12 potential setups as reported in Table 6.2, the Setup Planning procedure selects the minimum amount of ultimate setups

Table 6.1 The sample workpiece machining features

Feature	Feature type	$\cos(x^{wp})$	$\cos(y^{wp})$	$\cos(z^{wp})$
f_1	Chamfer	$-\sqrt{2}/2$	$-\sqrt{2}/2$	0
f_2	Blind hole	$-\sqrt{2}/2$	$-\sqrt{2}/2$	0
f_3	Blind hole	0	-1	0
f_4	Blind hole	0	0	-1
f_5	Blind hole	0	1	0

necessary to process all the machining workingsteps. The “Potential setups” column in Table 6.2 highlights how the same machining feature is allocated to several potential setups. The “Ultimate setup” column puts in evidence that this specific workpiece needs only three setups to be machined: the problem consists of selecting a set of potential setups able to perform the machining workingsteps required by the production problem. The decision about selecting a potential setup is influenced by all the rotated features which need a proper workpiece orientation to be machined.

The following rules ranked in order of priority have been considered to assign machining workingsteps related to rotated features to the ultimate setups:

1. assign a rotated feature workingstep to the setup which ensures the minimum tilt angle between the feature working direction and the standard placement direction;
2. assign this workingstep to the setup which contains the highest number of features to be processed in order to maximize the number of features to be machined within a setup.

Table 6.2 The sample workpiece setups

Standard placement direction	Standard placement cosines		Placement orientations	Potential setups	Ultimate setups
X	$\cos(zx) = 1$	(a)	$\cos(xz) = -1(+1)$; $\cos(yy) = +1(-1)$	f_1, f_2	–
		(b)	$\cos(yz) = -1(+1)$; $\cos(xy) = -1(+1)$	f_1, f_2	–
–X	$\cos(zx) = -1$	(a)	$\cos(xz) = +1(-1)$; $\cos(yy) = +1(-1)$	–	–
		(b)	$\cos(yz) = -1(+1)$; $\cos(xy) = +1(-1)$	–	–
Y	$\cos(zy) = 1$	(c)	$\cos(xz) = -1(+1)$; $\cos(yx) = -1(+1)$	f_1, f_2, f_3	–
		(d)	$\cos(yz) = +1(-1)$; $\cos(xx) = -1(+1)$	f_1, f_2, f_3	$\boldsymbol{f_1, f_2, f_3}$
–Y	$\cos(zy) = -1$	(c)	$\cos(xz) = -1(+1)$; $\cos(yx) = +1(-1)$	f_5	$\boldsymbol{f_5}$
		(d)	$\cos(yz) = +1(-1)$; $\cos(xx) = +1(-1)$	f_5	–
Z	$\cos(zz) = 1$	(e)	$\cos(xy) = +1(-1)$; $\cos(yx) = -1(+1)$	f_4	$\boldsymbol{f_4}$
		(f)	$\cos(yy) = +1(-1)$; $\cos(xx) = +1(-1)$	f_4	–
–Z	$\cos(zz) = -1$	(e)	$\cos(xy) = +1(-1)$; $\cos(yx) = +1(-1)$	–	–
		(f)	$\cos(yy) = +1(-1)$; $\cos(xx) = -1(+1)$	–	–

It is worth pointing out that the above reported rules are applied if the related workpiece orientation allows to machine the rotated features by means of a 4-axis machine. In general, the same rules are also applied to non-rotated features.

With reference to the sample workpiece, features f_1 and f_2 can be machined by exploiting the X placement direction; however the setups (X-a) and (X-b) are discarded because of the second priority rule reported above. Between the two potential setup configurations for machining f_1, f_2 and f_3, namely (Y-c) and (Y-d), the latter has been preferred because of the workpiece orientation. In fact, features f_1 and f_2 cannot be machined by a four-axis horizontal machining center using the (Y-c) setup, since the rotary table of a four-axis horizontal machine rotates around the machine y-axis (see Fig. 6.5). If no priority rule is activated, the Setup Planning procedure selects the workpiece orientation after a comparison between the workpiece and the setup face dimensions in order to optimize the amount of workpieces to be clamped onto the fixture face. Thus, the proposed Setup Planning procedure uses the information related to the workpiece in order to generate the setups; at the same time, it also needs the physical pallet geometrical information to maximize the number of workpieces to be located on a setup face. In order to reach an optimal setup face exploitation, it is necessary to develop an algorithm which is able to calculate the maximum number of workpieces to be clamped onto a setup face considering the workpiece orientation, the technological requirements and the priority rules. The Setup Face configuration sub-module performs this task.

6.4.2 Setup Face Configuration

The setup face configuration assumes a key role both for the setup planning and the pallet configuration activities. A setup face is defined as a single fixture face related to a specific physical pallet whereon a set of workpieces with identical

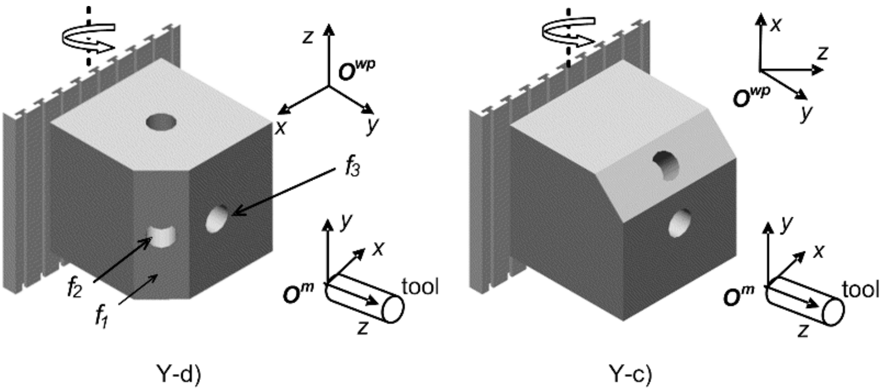

Fig. 6.5 (Y-d) and (Y-c) potential setups

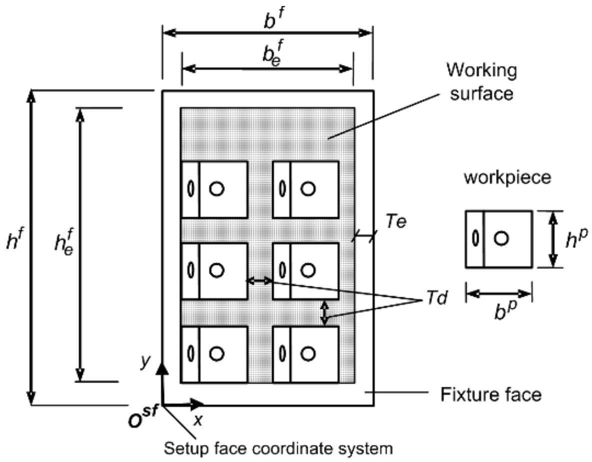

Fig. 6.6 The fixture face configuration for the sample workpieces

setup are clamped. A setup face also represents a geometrical constraint which involves both workpiece and fixture dimensions.

For each setup face the proposed procedure takes into account a tolerance edge *Te* which encircles the effective working surface; Figure 6.6 shows the working surface and the tolerance edge for such setup face.

The setup face working area represents the surface where one or more workpieces can be clamped in accordance to an established setup. In particular, assuming a fixture face as a matrix, the Setup Face Configuration (SFC) procedure computes for each potential setup the number of parts that are clamped along any row (x-direction with respect to the setup face coordinate system) and any column (y-direction with respect to the setup face coordinate system). The configuration must respect the tolerance distance *Td* between two adjacent workpieces.

The Setup Face Configuration procedure places the first part to be machined in correspondence to the left lower corner of the fixture face. Figure 6.6 reports an example of setup face configuration. The first step of the procedure consists of the comparison between the size of the setup face working surface and the area that should be occupied by the workpiece on said setup face.

Indeed, the size comparison between setup face and workpiece has to be performed on the basis of the whole set of potential setups, i.e. positions and orientations of the workpiece.

The next step of this procedure is the computation of the maximum number of workpieces that can be fixed on a setup face. Finally, if constraints related to rotated features do not exist, the potential setups which ensure an optimal exploitation of the setup face are selected as the ultimate setups.

The input and output data used for the algorithm performing the Setup Face Configuration procedure are reported in Tables 6.3 and 6.4, while the overall pseudo code of the procedure is shown in Table 6.5.

Table 6.3 Setup face configuration procedure: input parameters

Parameter	Description
h^p, b^p	Workpiece geometrical dimensions for a given placement
h^f, b^f	Fixture face geometrical dimensions
Te	Tolerance edge thickness
Td	Tolerance distance between two adjacent workpieces

Table 6.4 Setup face configuration procedure: output parameters

Parameter	Description
FCI_x	Fixture capacity index for any row;
FCI_y	Fixture capacity index for any column;
Np	Maximum number of workpieces to be clamped;

Table 6.5 Setup face configuration procedure: pseudo code

Step	Step description
Step 0	Calculate the effective fixture working surface: $h_e^f \leftarrow h^f - 2 \cdot Te$; $b_e^f \leftarrow b^f - 2 \cdot Te$;
Step 1	Dimension comparison: Calculate the maximum effective fixture face dimension: MAX_f; Calculate the minimum effective fixture face dimension: MIN_f; Calculate the maximum workpiece dimension: MAX_p; Calculate the minimum workpiece dimension: MIN_p; If $MAX\_p > MAX\_f$ then refuse the physical pallet; If MAX_f is along the x-direction then $MAX\_f \leftarrow b_e^f$; otherwise $MAX\_f \leftarrow h_e^f$; If MIN_f is along the y-direction then $MAX\_f \leftarrow h_e^f$; otherwise $MAX\_f \leftarrow b_e^f$;

Step 2	Calculate Fixture Capacity Index (FCI):
	If $MAX\_f = b_e^f$ then
	$FCI_x = \left\lceil \frac{MAX\_f}{MAX\_p} \right\rceil; FCI_y = \left\lceil \frac{MIN\_f}{MIN\_p} \right\rceil;$
	If $MAX\_f = h_e^f$ then
	$FCI_y = \left\lceil \frac{MAX\_f}{MAX\_p} \right\rceil; FCI_x = \left\lfloor \frac{MIN\_f}{MIN\_p} \right\rfloor;$

Step 3	Calculate Np:
	If $MAX\_p\ FCI_{x(y)} + (FCI_{x(y)} - 1)\ Td \leq MAX\_f$ then
	$NP_x = FCI_{x(y)}$
	else
	$NP_x = FCI_{x(y)} - 1$;
	If $MIN\_p\ FCI_{y(x)} + (FCI_{y(x)} - 1)\ Td \leq MIN\_f$ then
	$NP_y = FCI_{y(x)}$
	else
	$NP_y = FCI_{y(x)} - 1$;
	$NP = NP_x\ NP_y$;

6.4.3 Tool Path and Rapid Movements

In accordance with the ISO 14649 standard a workplan determines the final order of operations to be executed on a part: thus, since the first element in a workplan needs to be a rapid movement, in order to move the tool from its unknown start position to the start point of the first machining operation, an effective process configuration procedure should compute tool paths and rapid times associated with each configured pallet. The final stage of the Setup Planning procedure performs the tool path generation, i.e. an algorithm computes the total rapid feed rate time in relation to an established setup face. If a pallet can be loaded on a particular machine type, then the proposed algorithm starts the tool path computation. Since a pallet may be configured with different setup faces and must be loaded on a machine, several one-to-many relationships between a setup face and the machines arise from the tool path generation procedure. For each setup face associated with a machine, the first workpiece programmed in the tool path is the workpiece closer to the setup face left bottom corner, i.e. closer to the origin of setup face coordinate system. A different tool path should be defined for each feature of the workpieces clamped on the setup face. In Fig. 6.7 an example of tool path is plotted: it starts from the standby tool position and it visits the same feature f_3 for all the parts clamped on the setup face. Once the feature position related to the first workpiece has been detected on the setup face, the procedure is able to compute the distances along the x, y and z-directions that the tool has to cover moving from the standby position to the feature. The second part of the tool path computation regards the distance to be covered passing from a workpiece to another located along the same row or along the same column. The procedure considers the setup face as a grid and carries out a tool path which runs on consecutive rows, as reported in Fig. 6.7. Finally, the third part of the tool path brings it back to the standby position. As the overall tool path is determined, this information can be matched with the machine kinematics parameters (rapid feed rate speed and acceleration) to calculate the tool rapid feed rate times related to a setup face.

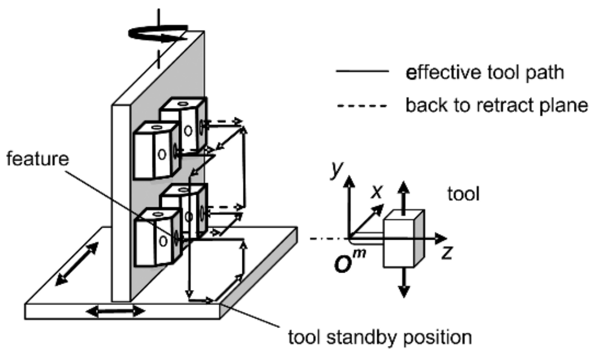

Fig. 6.7 The tool path definition for a setup face with 2 rows and 2 columns

6.5 Pallet Configuration

The Pallet Configuration procedure addresses the setup sequencing problem. A pallet type is defined by the information on the physical pallet and by the combination of its setup faces. Since for a given workpiece the relation between a physical pallet and its setup faces is one-to-many, an algorithm is required to generate the whole set of alternative pallet type configurations defined as combination of setup faces. In order to better explain the approach proposed to solve the pallet configuration problem, the analysis is referred to the sample workpiece previously introduced (Fig. 6.3). The following assumptions hold: (i) three types of physical pallets (PP01, PP02 and PP03) can be selected for the process configuration. Physical pallet PP01 (Angle plate) holds a single fixture face, PP02 (T-fixture) holds two fixture faces and PP03 (Tombstone) holds four fixture faces as described in Fig. 6.8; (ii) the sample workpiece, given the Setup Planning procedure results, can be clamped onto each of the available physical pallets. According to the setup face definition (e.g. a setup face is defined as a single fixture face related to a specific physical pallet whereon a set of workpieces with identical setup are clamped), for each physical pallet exists a one-to-one correspondence between setups and setup faces (see Sect. 6.4.2). Thus, for a workpiece which requires three setups there will be three distinct setup faces (e.g. *A, B* and *C*) for each physical pallet. Considering the combination of three setup faces and the three physical pallets (e.g. PP01, PP02 and PP03) a total amount of 9 setup faces can be identified:

1. PP01_A, PP01_B, PP01_C
2. PP02_A, PP02_B, PP02_C
3. PP03_A, PP03_B, PP03_C

Thus, each term of the above reported triplets represents a setup face related to a physical pallet. The Pallet Configuration procedure (PC) generates the whole set of setup face combinations by assigning a setup face to a specific

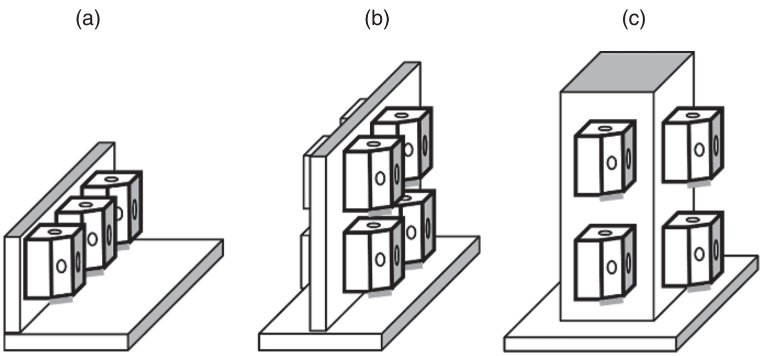

Fig. 6.8 The available physical pallets: (**a**) Angle plate, (**b**) T-fixture, (**c**) Tombstone

fixture face of a physical pallet. As reported in Sect. 6.3.2, a constraint assigns the same setup face to the symmetrical fixture faces of the pallets. For example, referring to the PP03 tombstone physical pallet characterized by four fixture faces, the Pallet Configuration procedure can configure the following combinations of setup faces:

1. PP03_A – PP03_A
2. PP03_B – PP03_B
3. PP03_C – PP03_C
4. PP03_A – PP03_B
5. PP03_B – PP03_C
6. PP03_A – PP03_C

Since each physical pallet has to be configured assuming a symmetrical fixture face configuration, the "PP03_A – PP03_B" solution means that the tombstone will be configured with two PP03_A setup faces and two PP03_B setup faces (e.g. see Fig. 6.9). The setup face combinations reported above are equivalent to the following six pallet configurations:

1. PP03_1: 4 (2 + 2) fixture faces arranged as setup face PP03_A.
2. PP03_2: 4 (2 + 2) fixture faces arranged as setup face PP03_B.
3. PP03_3: 4 (2 + 2) fixture faces arranged as setup face PP03_C.
4. PP03_4: 2 fixture faces arranged as setup face PP03_A + 2 faces arranged as setup face PP03_B.
5. PP03_5: 2 fixture faces arranged as setup face PP03_B + 2 faces arranged as setup face PP03_C.
6. PP03_6: 2 fixture faces arranged as setup face PP03_A + 2 faces arranged as setup face PP03_C.

The total number of combinations depends on the number of workpiece setups and on the number of fixture faces available on the physical pallet, as reported in Table 6.6; the value reported between parenthesis means that only for a workpiece with four expected setup faces it is possible to configure a tombstone where each face is characterized by a different setup. After the whole

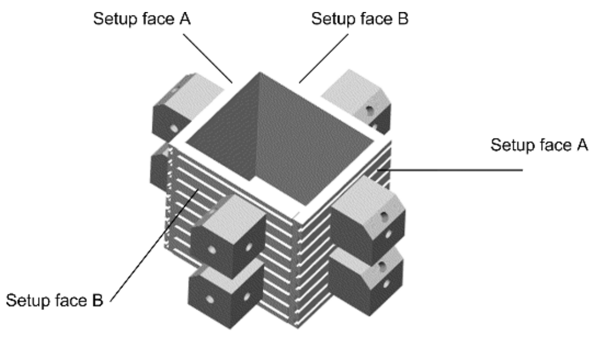

Fig. 6.9 Pallet PP03 configured with 2 setup faces A and 2 setup faces B (i.e. PP03_4)

Table 6.6 The maximum number of setup face combinations for each physical pallet

Physical pallet		Workpiece			
Type	Fixture faces	3 setups	4 setups	5 setups	6 setups
PP01	1	3	4	5	6
PP02	2	6	10	15	21
PP03	4	6	10(11)	15	21

set of alternative pallets has been configured, it is necessary to define the alternative process plans by sequencing setups while respecting the precedence constraints among the machining workingsteps.

6.6 Setup Sequencing

The final step of the "Mapping Requirements on Devices" procedure concerns the setup sequencing. Indeed, in this study the setup sequencing task is interpreted as the selection of a workplan resulting from a "pallet sequencing" activity which takes into account the precedence relations among the different pallets. Indeed, one or more technological precedence relations may occur among workingsteps within the same pallet (i.e. among workingsteps assigned to the same setup face), or among workingsteps assigned to different pallets. Precedence constraints among workingsteps assigned to the same pallet can be directly managed during the part program development and do not influence the workplan generation. On the contrary, precedence constraints among the workingsteps belonging to different pallets should be considered as an active constraint of the problem: thus, the main task of the Setup Sequencing procedure consists of generating alternative sequences of pallets which satisfy these precedence constraints. The feasible sequences of pallets provided by the Setup Sequencing procedure represent distinct process plans that can be defined as "workplans", in accordance to the STEP-NC standard. The input data of the procedure implemented to solve the Setup Sequencing problem have been introduced in Table 6.7, while the output data consist of the sequence of pallets; the pseudo code related to the algorithm is described in Table 6.8.

The sequencing algorithm runs a heuristic procedure that works by means of a random search for a limited number of iterations selected a priori by the user. To better describe how the setup sequencing procedure works, Table 6.9 summarizes the main information provided for the setup sequencing of the sample workpiece; in particular, the physical pallets PP02 (T-fixture) and PP03

Table 6.7 Pallet sequence generation procedure: input data

Parameter	Description
n_sf	Number of different setup faces allocated to a pallet
n_sf_max	Max number of different setup faces allowed within a sequence

Table 6.8 Pallet sequence generation procedure: pseudo code

Step	Step description
Step 1	Workplan generation procedure – mapping setup faces on pallets: for each pallet, its setup faces and the number of equal setup faces are identified by a relation table between the setup face and the pallet
Step 2	Mapping setups on setup faces: for each setup face, its corresponding workpiece setup is identified
Step 3	Mapping workingsteps on setup face: for each expected workpiece setup (which is also referred to a proper Standard Placement Direction), the workingsteps to be machined through that setup are individuated
Step 4	Pallet grouping: all the pallets which hold workpieces with the same setup represents a "pallet group"
Step 5	Workplan generation: A random search procedure generates sequences of pallet groups until the machining precedence relations existing among the workingsteps related to the setup faces allocated to those pallets are satisfied. At the end of the procedure, an ordered sequence of pallet groups are available for further elaborations together with a feasible workplan of machining workingsteps
Step 6	Pallet sequencing procedure – first pallet selection: $g = 1$; a pallet of the first pallet group ($g = 1$) is randomly selected as the first element of the pallet sequence. $g = g + 1$, $n\_sf = 1$ (if the selected pallet holds a single setup face); $n\_sf = 2$ (if the selected pallet holds two distinct setup faces); $n\_sf = 4$ (if the selected pallet holds 4 distinct setup faces and the workpiece needs only four setups)
Step 7	Additional pallet selection: if $n\_sf = n\_sf\_max$ then the pallet sequence has been generated, go to step 10, otherwise a pallet of the g-th pallet group is randomly selected as an additional element of the pallet sequence
Step 8	Setup face check: if the selected pallet is already included within the before $g-1$ selected pallets, then go to step 7, else accept the pallet: $g = g + 1$, $n\_sf = n\_sf + 1$ (if the selected pallet holds a single setup face); $n\_sf = n\_sf + 2$ (if the selected pallet holds two distinct setup faces); $n\_sf = n\_sf + 4$ (if the selected pallet holds 4 distinct setup faces and the workpiece needs only four setups)
Step 9	Sequence closing: if $n\_sf = n\_sf\_max$ then the pallet sequence has been generated, exit; else go to step 7

(tombstone) have been considered to illustrate this example of a pallet sequencing problem. Each row of the Table 6.9 refers to a pallet group; as stated before, each pallet group is related to an expected setup and to the workingsteps (WS) to be machined within that setup. The column named "setup" reports both the workpiece placement related information in terms of Standard Placement

Table 6.9 The setup sequencing for the sample workpiece: the pallet grouping

Group	Setup	Workingsteps	Setup faces	Pallet	Identical setup faces
1	Y SPD	WS_1, WS_2, WS_3	sf_1 $(=sf_4)$	PP02_1	2
				PP02_4	1
	$\cos(zy) = +1$			PP02_6	1
	$\cos(yz) = +1$			PP03_1	4
	$\cos(xx) = -1$			PP03_4	2
				PP03_6	2
2	−Y SPD	WS_5	sf_2 $(=sf_5)$	PP02_2	2
				PP02_4	1
	$\cos(zy) = -1$			PP02_5	1
	$\cos(xy) = +1$			PP03_2	4
	$\cos(yx) = -1$			PP03_4	2
				PP03_5	2
3	Z SPD	WS_4	sf_3 $(=sf_6)$	PP02_5	2
				PP02_3	2
	$\cos(zz) = +1$			PP02_5	1
	$\cos(xz) = +1$			PP02_6	1
	$\cos(yx) = -1$			PP03_3	4
				PP03_5	2
				PP03_6	2

Direction (SPD) and the specific workpiece placement orientation in terms of direction cosines.

The sample workpiece may be clamped with the same setup on the fixture faces of either the pallets PP02 and PP03: in fact, the three setup faces generated by the Setup Planning procedure can be assigned equivalently to the PP02 or the PP03 physical pallet; this means that the setup faces sf_1, sf_2 and sf_3 are equivalent to the setup faces sf_4, sf_5 and sf_6. The Pallet Configuration procedure designs pallets making full use of the provided setup faces, so it is possible to have different pallets configured with the same setup face. The last column of Table 6.9 takes into account the number of identical setup faces expected for each configured pallet. For example, the tombstone pallet PP03_4 is configured with two setup faces A and two setup faces B, i.e. there are two couples of symmetrical fixture faces. Furthermore, the T-fixture pallet PP02_6 has one setup face A and one setup face C.

Regardless of the precedence constraint existing among machining workingsteps belonging to different pallets, the pallet sequencing procedure generates effective pallets sequences as follows:

- PP02_1, PP03_2, PP03_3;
- PP03_1, PP03_2, PP03_3;
- PP03_1, PP03_5;
- ...
- PP03_6, PP03_2.

Then, in order to provide feasible pallet sequences just one pallet can hold the same setup face within a setup sequence: this means, for example, that the sequence PP02_1, PP03_4, PP02_3 should be declared as unfeasible because the setup face A would be included both in pallet type PP02_1 and pallet type PP03_4.

Although the number of expected setups for the sample workpiece is three, the pallet sequencing procedure may generate a sequence with a smaller number of elements due to the possibility of assigning different setup faces to the same pallet type. Finally, the pallet sequencing task can be considered as a double constrained permutation problem. In fact, the Pallet Sequencing procedure is able to find out feasible sequences of pallets respecting the following constraints: the precedence constraints among workingsteps which belong to different pallets and the setup face constraint which avoids duplicating any setup face on different pallets within a sequence.

6.7 Conclusions

This chapter has presented the "Mapping Requirement on Devices" procedure which consists of three interrelated modules: the "Setup Planning", the "Pallet Configuration" and the "Setup Sequencing" modules. The Setup Planning module maps the workpiece on physical fixtures in order to find out the optimal setups. The Pallet configuration module couples the setup faces with the physical pallets and the physical pallets with the machines: the output is a set of available pallets. Finally, the Setup Sequencing module generates a set of feasible workplans modeled as sequences of pallets to be loaded on the CNC machine. A detailed description of the "Mapping Requirement on Devices" procedure has been presented throughout the chapter with reference to a sample part to be machined.

The "Mapping Requirement on Devices" procedure which has been presented in this Chapter gives a research contribution in the fields of fixture selection/design and part modeling, positioning and orientation with reference to a "multi-setup" fixture configuration. In fact, in most of the literature the setup planning problem has been approached only by analyzing a single workpiece to be machined at a time. The proposed setup planning procedure performs a fixture face configuration wherein more than a part can be machined. Both multi-setup fixture configuration and setup generation have been integrated in a unique setup planning tool which takes into account only a well-defined set of potential setups for a part to be machined, while exploiting the workpiece envelope cube for defining its placement and its orientation on a fixture device.

In addition, since the setup sequencing problem is also affected by the multi-setup fixture configuration, an innovative approach has been proposed for solving the combinatorial constrained problem associated with the generation of feasible sequences of pallets.

Beyond what has been presented in this chapter, the research on process planning could address other important topics:

- The setup planning problem can be enhanced by assuming that the same feature can be processed by different operations and by means of different machining directions. As a consequence, the selection of alternative workingsteps would require an optimization procedure to minimize the number of setups needed by a given part, also enhancing the performance of the overall dynamic decision-making approach.
- The possibility to mount different part types on the same pallet fixture, in order to evaluate the tool change times impact on the overall pallet processing time.
- In order to enlarge the solution space in terms of alternative process plans, more orientations of the part could be considered whenever it is located on a fixture face; this strategy can be more interesting if machining centers equipped with multiple spindles or multiple tables are taken into account. In this case, significant effects should be primarily produced on the pallet configuration issue.
- Due to the high complexity of the setup sequencing problem in terms of combinatorial computation, additional and more efficient heuristic procedures could be developed and tested on the problem.

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Chapter 7
Design of Focused Flexibility Manufacturing Systems (FFMSs)

Walter Terkaj, Tullio Tolio and Anna Valente

Abstract Manufacturing systems design must provide effective solutions to cope with the demand during the whole system life-cycle. The problem consists of selecting the appropriate set of resources which best fits the requirements of the addressed production problem. When the demand is characterized by a family of products undergoing technological and volume modifications, the system design process becomes quite complicated. Starting from present and forecasted information, machine tool builders have to design systems endowed with the flexibility and reconfigurability levels that enable the system to face the production problem variability during its life. In spite of the relevance of this topic, there is a lack of tools to explicitly design system flexibility and reconfigurability considering the uncertainty affecting the problem. By addressing two main types of uncertainty, i.e. demand variability and resource availability, this chapter presents a solution method based on multi-stage stochastic programming, to support the design of new manufacturing system architectures whose level of flexibility is focused on the specific production requirements. The problem variability is modeled through scenario trees and the solution is a capacity plan with an initial system configuration and possible reconfigurations. Testing experiments have been carried out considering an industrial case to study the benefits that this approach can offer to machine tool builders.

Keywords Manufacturing system design · Focused Flexibility Manufacturing Systems – FFMS · Stochastic programming

7.1 Introduction

Manufacturing system design is a highly critical task because it entails the consideration of different criteria related to economy, finance, technology, management, customer satisfaction and human resources involving both

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quantitative and qualitative aspects, as highlighted by Manassero et al. (2004). Moreover, the impact of external uncertainty (e.g. demand volumes and technological characteristics of the products) and internal uncertainty (e.g. resource availability) should be taken into account during the design phase. As a consequence, the manufacturing system design problem must refer to a planning horizon embracing the whole system life-cycle.

As introduced in Chap. 1, the problem of manufacturing system design is addressed both by machine tool builders and system users. The task of the machine tool builder is to identify a set of alternative system configurations which fit the production requirements with different cost and performance. The system user evaluates the alternative system configurations and defines the timing of acquisition of the resources, thus planning its system life-cycle (see Chap. 8). Even if the design of the whole system life-cycle complicates the problem, it represents an opportunity for the machine tool builders. Indeed, future system reconfigurations are a revenue option that machine tool builders should analyze when preparing an offer that can be profitable not only at the time of installation but also in the long-term.

In this chapter the analysis focuses on the design activity carried out by the machine tool builder who has to select the set of resources to cope with the production problem of his potential client. As a consequence, in this chapter the system designer corresponds to the machine tool builder.

During the design process, production variability and uncertainty are typically handled by enhancing the flexibility degree of production systems. However, even if system flexibility is often judged as a fundamental requirement for firms, it is not always a desirable characteristic because it requires relevant investments which can deeply impact on the firm profitability. Indeed, an analysis of industrial cases highlights that system flexibility is not always essential (Matta et al. 2001). For instance, production problems characterized by mid-high demand volumes of a low variety of products which undergo few modifications should be faced by production systems that do not require the highest level of flexibility. The system flexibility should be customized on the production requirements, aiming at the optimal trade-off between productivity and flexibility. The strategy of customizing system characteristics on present and forecasted production requirements gives an advantage to system users because it is possible to reduce the investment effort thus increasing the profitability. Focusing the system flexibility offers advantages to machine tool builders as well, because the competitiveness can be increased by offering innovative and cost effective solutions.

Production systems that give an answer to the need of customizing the system characteristics on the production requirements belong to the class of Focused Flexibility Manufacturing Systems – FFMSs (see Chap. 1). This new class of manufacturing systems allows to answer to the production problem by guaranteeing the optimal trade-off between productivity and flexibility (Ganzi and Tolio 2003; Tolio and Valente 2007; Cantamessa et al. 2007; Tolio et al. 2007). Information about the required level of system flexibility can be exploited both by machine tool builders, when generating a bid, and by system users, when evaluating bids. However, it must be noted that these two actors can have different objective functions and therefore their optimal solutions could not coincide. Indeed, a machine tool builder aims at maximizing his profit when selling a system, while a system user aims at minimizing the investment cost (Terkaj and Tolio 2007).

The complexity of the system design process suggests the need of decision support tools to tackle the previous issues and to make this activity more efficient and effective (Matta et al. 2005). A higher efficiency is obtained because it is possible to explore a wider range of system solutions, while a higher effectiveness is reached because the machine tool builder can increase its expected profit. Moreover, a formalized approach to system design can help a machine tool builder to quantitatively justify the configuration decisions, i.e. the selection of particular resource types.

On the basis of these observations, this chapter proposes a model to design FFMSs consisting of CNC machine tools with automated material handling devices by considering both economic and technological issues. However, this approach can be easily extended to others Automated Manufacturing Systems (e.g. Flexible Transfer Lines, Flexible Manufacturing Systems, Reconfigurable Manufacturing Systems, etc.). The proposed design model aims at defining a plan with an initial system configuration and future reconfigurations to cope with the changes affecting the external and internal environment. Uncertainty related to these changes will be modeled by means of a stochastic programming approach.

The content of this chapter is structured as follows. The next section presents a literature review on the manufacturing system design topic. The problem statement is formulated in Sect. 7.3. The system design approach is introduced in Sect. 7.4, while Sects. 7.5, 7.6, 7.7 and 7.8 present different system design models that aim at considering different issues. Section 7.9 provides the results of the testing activities. Finally, Sect. 7.10 provides concluding remarks and future developments of the whole system design approach.

7.2 Literature Review

As anticipated in the introduction, manufacturing system design represents a complex task since it deals with many different aspects. This explains the lack of methodologies which allow to jointly consider its different sub-problems at the same time. A literature review of the papers addressing the topic of manufacturing system design has already been presented in Chaps. 1 and 3, paying attention to manufacturing systems endowed with flexibility. In this section the focus is on system design methodologies and in particular on those papers that present methods belonging to two main research areas: capacity planning methods and manufacturing system design methods performing a technological analysis both of the production problems and of the system resources.

Regarding the capacity planning methods, Matta et al. (2001) provided a framework to design Advanced Manufacturing Systems capacity taking in consideration different factors such as firm strategy, market uncertainty, uncertainty regarding competitor strategies, available system architectures and types of technologies. The capacity planning problem has been also addressed by Asl and Ulsoy (2002, 2003) who presented an optimal policy for the capacity management problem. They provided a model which considers both capacity expansion and reduction problems adopting the Markov decision theory. Recently, Matta et al. (2008) presented an evolution of the approach by Asl and Ulsoy (2003) where the effect of the ramp-up phenomenon is explicitly modeled; the authors have proved that ignoring the ramp-up effect in the decision process can significantly increase the overall costs. Amico et al. (2006) proposed a capacity planning model for Reconfigurable Manufacturing Systems (RMSs) modeling the investment decisions through the joint application of the Discounted Cash Flow (DCF) and the Real Options Analysis (ROA) techniques. Deif and ElMaraghy (2006) developed a Genetic Algorithm (GA) technique for generating an optimal capacity schedule for RMSs; the capacity level and the cost of the capacity schedule of RMSs are related to the cost of system reconfigurations. Thus, the cost-effective implementation of RMSs relies on decreasing the cost of system reconfigurations.

The problem of evaluating the impact of technological issues on the system design has been addressed by Shin et al. (1997) who proposed a decision support model for the design of Flexible Manufacturing Systems, with the goal of maximizing the profit of the system. The authors highlighted that in many system design approaches the part types to be produced are considered as given; then, this input information is used to determine an optimal system configuration. However, more realistic solutions can be obtained when the interaction between candidate part types and configurations are explicitly modeled. Park et al. (2001) addressed the problem of FMS design developing a hybrid approach by (1) simultaneously considering design and operational parameters, (2) modeling performance measures of the FMS using design of experiments and regression analysis, and then (3) achieving optimal levels of multiple performance measures through a compromise programming problem.

These two main research areas have been rarely merged by developing integrated design methods that jointly consider technological and demand information. Ganzi and Tolio (2003) proposed a system design method that provides as output manufacturing system configurations whose level of productivity and flexibility is tuned on the production needs of the firm. The developed approach starts from a detailed analysis of technological and demand data. At first, the part mix is analyzed to define clusters of machining operations that require machine tools with the same technological and functional characteristics. Then, the information content of each cluster is used to solve the system configuration/reconfiguration problem. The design problem becomes even more complex if the manufacturing system must be designed to cope with changes of production requirements, taking into account both present and future production problems. This topic has been addressed by Tolio and Valente (2006, 2007, 2008) who introduce the concept of focused flexibility in manufacturing. The authors have shown that the breadth and diversity of the selectable resources have an important impact on the expected profitability of the designed systems. Indeed, a rich resource catalogue gives to the system designer much more options to answer to the production requirements in a cost-effective way. The same authors developed a design framework that, starting from the production problem analysis and formalization, gives as output the number and type of resources that are needed to face the present and forecasted production requirements.

7.3 Problem Statement

The FFMS design problem represents the central topic of the manufacturing system design framework presented in Chap. 1 by means of IDEF0 diagrams. As anticipated in the introduction of this chapter, herein the activity of system design is carried out by machine tool builders, keeping as reference the double design perspective of the machine tool builder and of the system user (see Sect. 1.5).

The manufacturing system design problem consists of selecting the best set of resources to satisfy the production requirements during the whole system lifecycle with the maximum expected profit. Since Automated Manufacturing Systems (AMSs) and in particular FFMSs are considered, the resources consist of CNC machine tools, transporters, load/unload stations, pallets and tools. In particular this book focuses on systems producing prismatic components which can be loaded on pallets to be machined on CNC machines. Pallets are assumed to be easily moveable among machines by proper automated transport systems. The cost of the resources which can be selected in the design phase depends on their architecture and their performance. The system design process can start from green field or can regard an existing production system. In the first case, the whole set of resources must be purchased. In the second case, it could be necessary to purchase just a subset of the required devices and to integrate new resources within the existing system.

The tooling system configuration problem is not considered in this book since this activity can be addressed at a lower level in the system design hierarchy. Therefore the FFMS design model presented in the following sections does not select the number and type of tools. For an analysis of the tooling system configuration problem please refer to Grieco et al. (1995), Colosimo et al. (2002), Matta et al. (2004) and Buyurgana et al. (2004).

Besides the set of selectable resources, the machine tool builder needs information about the demand and the feasible process plans to machine the products. In particular, the demand is characterized by a set of products with their demand volumes and technological features. Volumes and product features can evolve over time, e.g. products may be modified, new products can be introduced and demand volume can change. Moreover, demand volumes can also be subject to mid-term variability. Short-term variability is not considered in this work since it mainly impacts on the system management. Information regarding the technological requirements of products to be machined determines the selection of resource types, while information regarding production volumes drives the choice of the number of resources. The modeling of the production problems will be further addressed in Sect. 7.3.1.

Process plans are an important input of the system design problem, since they specify how the resources can be used to produce the various part types. It is assumed that such technological analysis has already been carried out so that the machine tool builder can choose from a set of alternative process plans generated considering all the possible resources (Contini and Tolio 2004). Indeed, process planning defines the necessary operations and the setups required to execute the operations. Operations and setups are then assigned to pallets that will be loaded on selected subset of machines. Therefore at system level a process plan can be thought as a sequence of pallets that must be processed to obtain the final product (see Chap. 6). Selected process plans must be tested before starting production by checking if all their operations are properly executed on the assigned machine type. This testing phase has a cost because it reduces the plant capacity and it usually requires the presence of an operator.

The output of the FFMS design consists in the selection of resources and process plans to be implemented in a system configuration. Since the production problem evolves over the planning horizon, it can be necessary to properly reconfigure the system. A set of possible reconfigurations can be defined according to the future outcomes of the random variables affecting the problem. Therefore, the output of system design should be a capacity plan with an initial system configuration and a set of possible reconfigurations affecting hardware (e.g. acquisition/dismission of resources) and/or software (e.g. change of process plans) resources of the system.

7.3.1 Modeling of Production Problems

The design of evolving manufacturing systems requires a careful study of the production problem over the whole system life-cycle. Present and future information must be taken into account by the decision maker to provide the most efficient system solution. The manufacturing system must be able to react to changes in the production problem; as described in Chap. 1, this reaction can be accomplished by using the already existing characteristics of the system or by adopting system reconfigurations. If reconfigurations are needed, then the system must be endowed with the necessary enablers, e.g. modularity, scalability, etc. (Wiendahl et al. 2007).

Production problems can be considered as a combination of mixes of products that evolve during the observed horizon. The evolution of the products depends both on the market requirements and on the company strategy (Tolio 2006). The definition of the production problems should be as precise as possible because it deeply impacts on the system design activity. Since managing information in an evolutionary perspective can be quite complex, a scenario tree representation can help to simplify the analysis. The scenario tree adopted in this book (Fig. 7.1) is a directed graph composed of nodes representing the outcomes of a set of random variables defining the production problem characteristics. Each level of the scenario tree represents a time period (e.g. six months, one year, etc.). Each node contains the information associated with a certain time period and it is characterized by a unique parent node and by a realization probability. A sequence of linked nodes in the tree models the information evolution along the planning horizon. Each path from the root node to a leaf node in the last time period identifies a scenario. In Fig. 7.1, scenario nodes are represented as circles; in particular, nodes of Scenario 1 are enclosed by a dashed rectangle, while nodes of Period 2 are enclosed by a dotted oval. The scenario nodes are positioned at the beginning of the time period that they are representing.

Moreover, a single node could be composed of many short/mid-term (e.g. daily, weekly or monthly) production problems. For instance, subcontractors must produce in the same system components which are sold to different customers with different due dates, so that the system usually does not face the same production problem every day. Therefore each scenario contains one ore more short/mid-term production problems which are represented as dotted circles in Fig. 7.2. Chapter 4 has already provided a detailed description and formalization of the scenario tree (Sect. 4.4).

Short- and mid-term production problems characterizing the demand can be simplified through a mathematical analysis. Indeed production problems inside each scenario node can be encompassed by a convex polyhedron as represented in Fig. 7.3, where the axes of the diagram represent the quantities of the two product types (product *A* and product *B*) composing the part family. A system

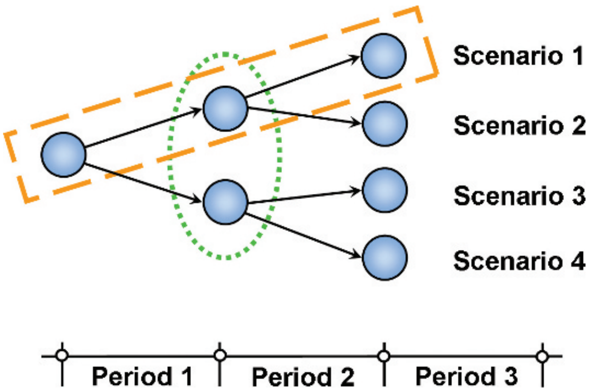
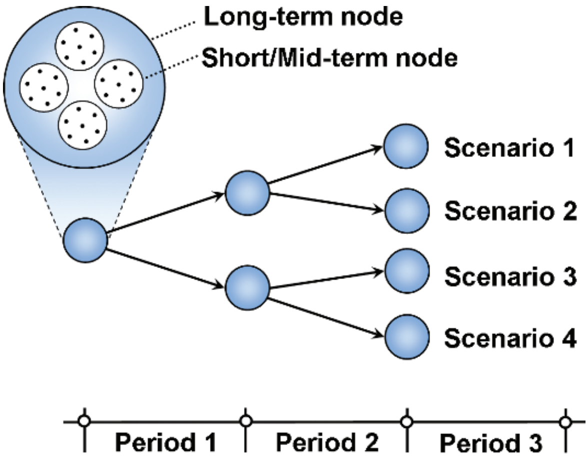


Fig. 7.1 Scenario tree representation

Fig. 7.2 Extended Scenario tree representation



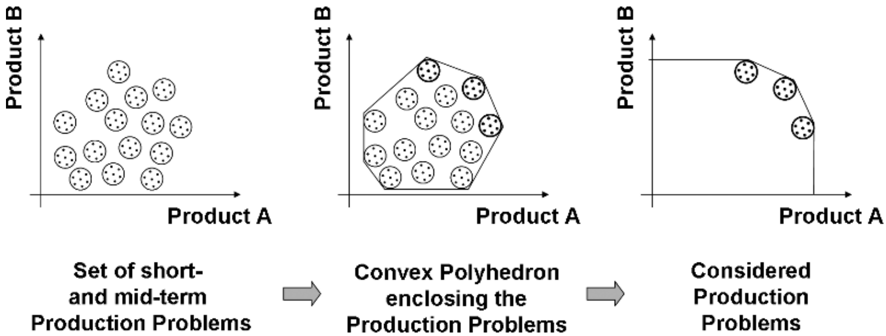


Fig. 7.3 Production problem analysis and simplification

that is able to cope with the production problems at the vertex of the polyhedron can also face all the production problems inside the polyhedron. Therefore, by evaluating only production problems at the vertex of the polyhedron it is possible to simplify the system design problem.

The generation of a scenario tree for the problem of manufacturing system design and its link with the manufacturing strategy is addressed in Chap. 5 of this book. Depending on how the production problem variability has been modeled, different system design models can be developed as it will be show in Sects. 7.4.1 and 7.5.

7.4 System Design Approach

Terkaj et al. (2008) have suggested that a complete system design approach should be developed taking in consideration the *Basic Flexibility Levels* (i.e. Flexibility, Reconfigurability and Changeability) and *Basic Flexibility*

Dimensions (i.e. Capacity, Functionality, Process, Production Planning) which have already been described in Chap. 3. Levels and dimensions can help to define the constraints that match the requirements of the production problems with the selectable resources.

A manufacturing system design approach considering the *Basic Flexibility Levels* must be able to:

- model both the dynamicity and stochasticity of product life-cycle and use this information as input of the system design model;
- plan the system life-cycle, thus defining the initial system configuration and possible future reconfigurations.

Therefore, it is necessary to clearly separate the configuration decisions which must be taken immediately from those which can be taken later. These issues can be fully addressed adopting the stochastic programming technique (Birge and Louveaux 1997). The application of this technique is presented in Sect. 7.4.1.

The FFMS design approach addresses a set of issues that can be defined and grouped according to the *Basic Flexibility Dimensions*. The *Process* issues deal with:

- the choice of the process plans among a set of alternatives;
- the validation of new process plans;
- precedence and tolerance constraints among the operations.

The FFMS design approach has to model also *Functionality* issues such as:

- the assignment of the operation types to the selected resource types;
- the assignment of the pallet types to the selected resource types.

Finally, the FFMS design approach has to address the following issues that are related to the *Capacity* of the manufacturing system:

- modeling of resource capacity and resource usage by the operations. The resource types are machine, carrier, load/unload station and pallet;
- possible reductions in the availability of the resources;
- modeling the shortfall production of the system.

The resource selection and the operation assignment problems are strictly related in the case of FFMS design. Therefore it is necessary to integrate these aspects in order to obtain effective system solutions.

All the issues previously described have been addressed by the proposed system design methodology through the formulation of proper constraints (see Sect. 7.6.3). Acting on the constraints it is possible to implicitly define the flexibility embedded in the system. The constraints have been developed according to some assumptions regarding products, processes, resources and economic issues that are detailed in Sect. 7.4.2.

Finally, the manufacturing system design approach must be able to use all the relevant input information and provide as output the necessary data. The specification of the input and output information of the FFMS design approach are described in Sects. 7.4.3 and 7.4.4, respectively.

7.4.1 Stochastic Programming

A production system designed considering a deterministic environment can yield a lower performance than what is expected because of the uncertainty affecting the production environment. Stochastic programming (Birge and Louveaux 1997) can be used to develop a system design model addressing the topic of co-evolution of production problems and production systems. Indeed stochastic programming allows to model uncertainty using a scenario tree approach. The same methodology takes into account that initial decisions can be modified by future recourse actions according to the realizations of the different scenarios. Therefore a stochastic programming approach can exploit the definition of production problems through scenario trees and gives as output the system configurations and reconfigurations by defining different decision stages.

When a stochastic programming model is solved, the expectation of an objective function is optimized against the considered realizations of the random variables, while respecting a set of constraints. Therefore, initial decisions are followed by observations of uncertain parameters which are gradually revealed over time. The evolution of the products is modeled by means of the scenario tree that has been described in Sect. 7.3.1.

When stochastic programming is adopted to solve a stochastic problem modeled with a scenario tree, then it is possible to formulate also a decision tree. The number of stages which are considered in the decision tree can be different from those of the scenario tree and this means, in the case of system design, that the decision maker can model the availability of system reconfiguration options in one or more periods. Depending on the number of times that the decision maker can revise the designed system solution, it is possible to model single-, two- or multi-stage problems.

In a single-stage design model all the decisions must be taken at the beginning of the planning horizon. In particular, a single-stage formulation leads to determine a system configuration which is able to cope with the whole set of production problems, both present and future (see Sect. 7.5). This means to take a single decision in order to face the input scenario tree, as illustrated in Fig. 7.4 where the decision node is represented as a striped circle.

A two-stage stochastic formulation of the FFMS design approach (see Sect. 7.5) allows to model the reconfiguration of the manufacturing system during a future time stage. The initial system configuration is designed taking into account both the deterministic data related to the present production problem and the data related to the production problems that can occur in the future. This decision is applied “Here&Now” and is equal for all the forecasted scenarios.

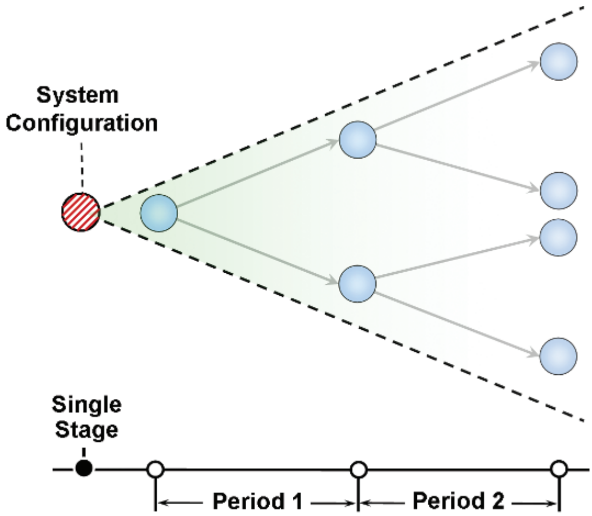


Fig. 7.4 Single-stage decision

When information about future production problems is disclosed, then the system designer can take recourse actions to cope with the changes in the environment. In a two-stage stochastic programming model all these recourse decision are explicitly defined and each scenario has a different optimal second stage solution. In Fig. 7.5 the decision nodes are represented again as striped circles, while the nodes of the scenario tree as full circles; the second stage decisions (i.e. system reconfiguration decisions) are implemented only after the disclosure of the stochastic information about future time periods.

If compared to the single-stage formulation, a two-stage model provides more efficient system solutions since the decision maker has the opportunity

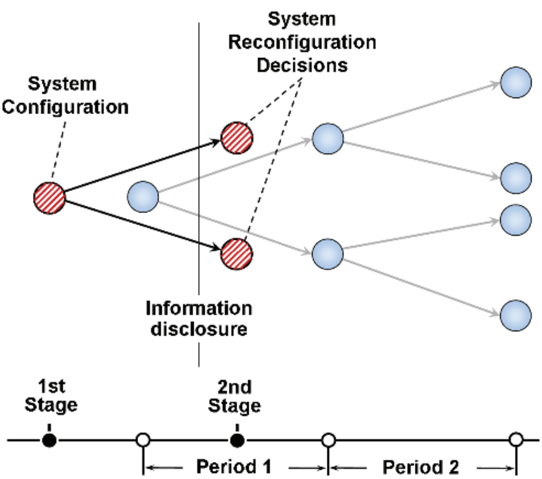


Fig. 7.5 Two-stage decision tree

to customize the system configuration on the real production requirements. The two-stage decision procedure can be applied over a long time horizon through a rolling approach. In this case, as soon as the stochastic information is disclosed, the two-stage model is launched again shifting the planning horizon by one period and considering as given the system configuration previously obtained. Therefore the second stage solutions can be considered as reconfiguration options since they will not be necessarily implemented. In Fig. 7.6 the second stage corresponds to the first stage of the new system design problem that is launched after the disclosure of the stochastic information.

In a multi-stage formulation the decision variables are divided into different time stages (see Sect. 7.6). The correspondence between the nodes of the general scenario tree (Fig. 7.1) and the nodes of the decision tree (Fig. 7.7) is at most one-to-one: indeed it could happen that the number of decision tree stages is lower than the number of stages of the considered scenario tree and/or some nodes of the decision tree are aggregated when building the decision tree. Decision variables associated with a stage are replicated for every node belonging to that stage. In a multi-stage approach it is possible to model all the system reconfiguration options that can be implemented when the actual production information is disclosed.

A multiple decision formulation represents the most complete technique in production contexts characterized by frequent changes since it guarantees a

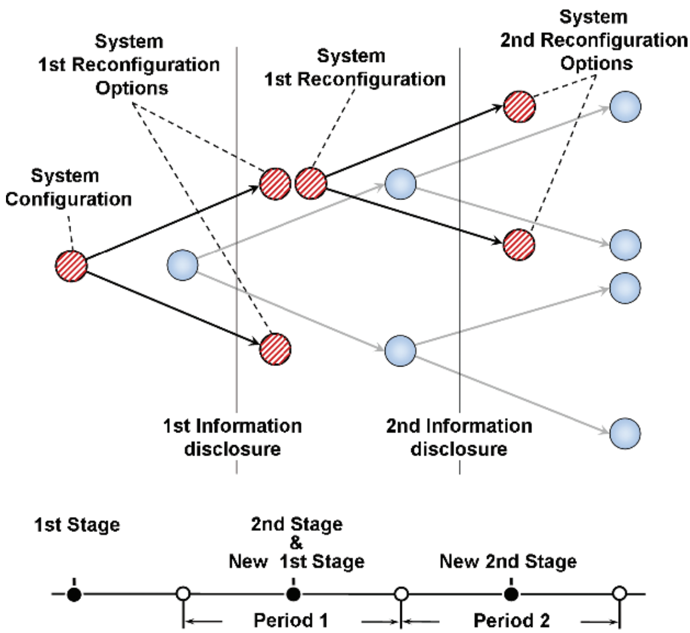


Fig. 7.6 Two-stage approach with rolling horizon

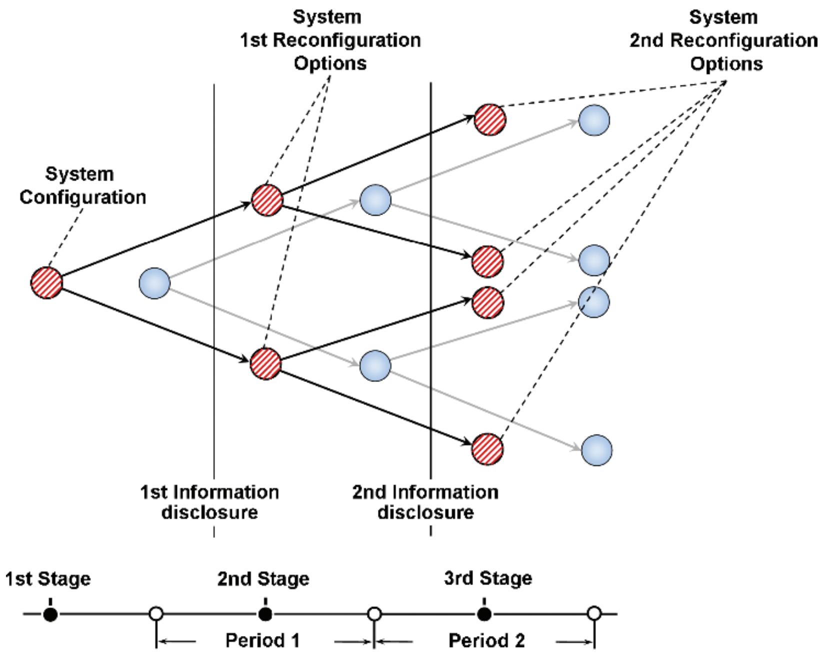


Fig. 7.7 Multi-stage decision tree

precise modeling of the future evolutions and of the way to cope with them. However, stochastic programming models can require a significant computational effort. To face this issue some algorithms have been developed to decompose the problem and solve it in a more efficient way (Laporte and Loveaux 1993; Sen and Higle 2005; Sen and Sherali 2006).

7.4.2 Assumptions

The system design approach that is proposed in this book can be applied to the general domain of Automated Manufacturing Systems. However, the system design models presented in this chapter have been developed paying attention to the particular case of Focused Flexibility Manufacturing Systems (FFMSs). The FFMS design models presented in the next sections have been developed adopting the following assumptions about products, processes, resources, economic issues and boundary conditions.

The assumptions related to the products are:

- Long-term variability and evolution of the demand of the products is modeled by means of a scenario tree.
- Short- and Mid-term variability of the demand is not considered. Therefore the scenario tree modeling the production problem is simplified as reported in Fig. 7.1.

The assumptions related to the processes are:

- The workpieces are mounted on pallets by means of fixtures that have the function of providing stability to parts during the machining operations. The fixtures are usually, but not always, dedicated to a single type of workpiece. The shape and dimensions of the pallets depend on the technological requirements of the type of workpiece and on the characteristics of the machines (e.g. number of axes and working cube).
- When a process plan is selected for a type of workpiece it is necessary to test the sequence of machining operations in order to fine tune the part programs on the machining centers. This process plan validation and refinement has a cost which is considered in the system design model.
- The machining operations composing a process plan are subject to precedence and tolerance constraints. This aspect influences the routing and assignment of the pallet types to the machine types.
- According both to the system architecture and to the pallet configuration, a pallet type can be processed on one or more machine types. For instance, in an FFMS a pallet could be processed by a traditional machining center and by a dedicated machine.

The assumptions related to the system resources are:

- The selection of the type of transporter is made ex-ante because it is related to strategic decisions about the layout of the manufacturing system. For instance the system designer could choose between a pallet transporter and a part conveyor. In this work it is assumed that there is an automatic pallet transporter (i.e. carrier) in the system: it moves pallets from/to the load/unload stations, the machines and the pallet buffer.
- There are automatic or semi-automatic pallet load/unload stations in the system. An alternative option would be to design six-degree-of-freedom clamping robots which load and unload parts between a part conveyor and a fixture equipping the machining center the machining centers. However, this latter option has not been taken into account in the design model.
- For the sake of simplicity the choice of the type of load/unload station is made ex-ante. This assumption can be easily relaxed with minor changes in the model.
- The configuration of the tool magazine is not considered in the FFMS design model since it is usually addressed at a lower level in the system design hierarchy.

The assumptions related to economic issues and boundary conditions are:

- The purchasing cost of the resources is assumed constant over time. This assumption can be relaxed by machine tool builders when applying the model to real problems. In fact, the evolution of the resource prices can be often estimated by machine tool builders, but this information is not spread because of privacy policy. For the same reason, also the selling price of the dismissed resources is assumed to be constant over time.

- If the manufacturing system is not able to satisfy the demand, then the firm incurs into penalty or outsourcing costs to face the production shortfall.
- Cash flows are discounted in order to consider changes in the value of money.

7.4.3 Input

Two phases characterize the design approach. The first phase consists of collecting and formalizing information on current and future production problems whereas the second phase deals with the application of design models to the gathered information.

The necessary input information of the manufacturing system design problem regards:

- the family of products to be machined, in terms of technological characteristics and demand volumes (see Sect. 4.4 and Chap. 5);
- how the products can be processed, i.e. the set of (alternative) process plans together with their operations and pallet types required to produce the workpiece types (see Sect. 4.6 and Chap. 6);
- the set of available resources which can be selected for the designed system (see Sect. 4.5).

All these data have been formalized according to the data structure presented in the tables of Chap. 4 to enable the exchange of information among the different modules in the system design architecture (see Chap. 1). Manufacturing system design requires information about all the three areas presented in Chap. 4: product, process and production system.

The information about products consists of the set of products (i.e. workpieces; Table 4.1), the technological characteristics of the products (i.e. machining features; Table 4.2), the present and possible future demand volumes (i.e. demand scenarios; Tables 4.3 and 4.4).

The information about processes defines how the available and selectable resources can produce the demanded workpiece types. The required data include the machining workingsteps (Table 4.16), the pallet types (Table 4.18) and the process plans (i.e. the workplans; Table 4.17).

The information about production systems consists of the current system configuration if the design does not start from green field (Table 4.5). Moreover, it is necessary to describe the set of resources which are in the system or that can be acquired: machining centers (Table 4.8), carriers (Table 4.9), load/unload stations (Table 4.10), tools (Table 4.11), tool carriers (Table 4.12) and physical pallets (Table 4.13).

The set of data concerning the products and processes can be affected by uncertainty. The ability to forecast future changes in terms of technological and production information strongly influences the flexibility level that is designed into the system. For instance, limited information regarding future changes can lead to design a system characterized by a high flexibility degree. Conversely, perfect information about future changes allows to customize the degree of flexibility in the system.

7.4.4 Output

The main output of the design models consists in the set of resources composing each system configuration. In addition, decisions about process planning must be taken; these decisions link each system configuration with a set of workplans (Table 4.17) and a set of assignments of pallets and machining workingsteps to the selected machining centers.

In Sect. 7.3.1 it was shown that the production requirements can be mathematically modeled by the definition of a convex polyhedron representing all the production mixes that could occur. In a similar way, a given system configuration can be characterized by the possible combinations of production volumes that the system can yield. The domain of admissible production volumes can be thought as a n-dimensional space which is bounded by a set of hyperplanes and where the axes correspond to the product quantities. The hyperplanes derive from the capacity constraints which are formulated within a system design model (e.g. see Sect. 7.6.3). The concept of hyperplane has already been introduced in Chap. 4 (Table 4.7).

An example of manufacturing system characterization through hyperplanes is shown in Fig. 7.8.a; in this case, the space is 3-dimensional since there are three part types in the part family (i.e. Product A, Product B and Product C). The manufacturing system consists of four resources (i.e. two machines, one carrier and one load/unload station) and each plane is associated with a resource type.

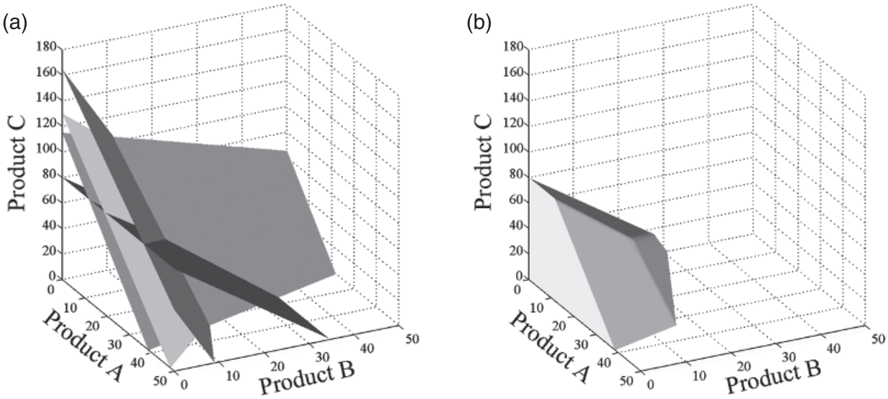


Fig. 7.8 (**a**) Hyperplanes bounding the admissible domain (**b**) Admissible domain of the production system

The admissible domain of the production system is the polyhedron (Fig. 7.8.b) bounded by the planes and having the origin of the axes as one of its vertices.

Concluding, a manufacturing system can properly address a production problem only if the polyhedron of the admissible domain contains the polyhedron modeling the domain of the possible demand levels.

7.5 FFMS Design Models

The system design approach presented in the previous section has been adopted to formulate a set of FFMS design models; these models apply different types of stochastic approach (see Sect. 7.4.1) and meet different requirements of the system designer. This section presents a brief description of the single-stage model (Tolio and Valente 2006) and the two-stage stochastic model (Tolio and Valente 2007), highlighting their key points and possible applications. This should facilitate the understanding of the multi-stage stochastic model (see Sect. 7.6) and its possible extensions (see Sects. 7.7 and 7.8).

In the single-stage model (Tolio and Valente 2006) the system designer takes all the decisions at the beginning of the planning horizon. Therefore, the decision maker must select the set of machines, carriers and load/unload stations which are able to satisfy the whole set of possible production problems, while minimizing the investment costs. This particular model could fit the requirements of subcontractors; indeed they typically have to satisfy different production problems with the same production system. Moreover, a single-stage design model could be applied when the system user has partial information about the production problems to be faced in the future but he wants to determine the upper bound, in terms of costs and flexibility, of a system configuration which can meet all the future scenarios (Fig. 7.4). Since the proposed system must be feasible in all the scenarios it is not necessary to estimate their realization probability.

The two-stage stochastic formulation of the FFMS design problem has been developed in order to take into account the uncertainty affecting the production information. The complete formulation of the two-stage stochastic programming model is reported in the paper by Tolio and Valente (2007). By analyzing the design problem formulations a dominant feature is the importance of the timing of flexibility acquisition. Indeed, the planning of flexibility acquisition over time represents a key factor especially for companies whose profitability can be jeopardized by high system investment costs. This is why a multi-stage approach (see Sect. 7.6) can offer a better modeling of the problem.

However, the advantages related to postponing the investments can be reduced by the need to face more system ramp-ups whose economic impact is not negligible. A system "Total Cost" analysis should be developed to correctly plan the timing of flexibility acquisition (see Sect. 7.7).

A common feature of all these models is that they aim at minimizing system costs. This choice is mainly related to the need of the machine tool builder to know the optimal configuration of such a production system, i.e. the set of resources which satisfy the production problem with the minimum economic effort. In this sense, the machine tool builder can interpret that solution as a lower bound on which he could start to evaluate his own revenue options. Section 7.8 will present an extension of the multi-stage approach based on the maximization of the expected profit is presented.

7.6 Multi-Stage Stochastic FFMS Design Model

The development of a multi-stage stochastic programming model allows to design the whole production system life-cycle taking into consideration uncertain information represented by complex scenario trees (Fig. 7.7). Indeed, a two-stage formulation does not provide competitive solution in production contexts affected by frequent changes over a long horizon. Even if the two-stage formulation can be improved adopting a rolling approach, only a multi-stage approach offers the possibility of jointly modeling all the system changes and the time in which they occur.

In the multi-stage stochastic model the system designer starts from the analysis of the scenario tree which represents the evolution of the production problem over the planning horizon. Afterwards he defines the decision tree to cope with the present and forecasted production problems belonging to well-defined time periods.

The model gives as output the set of decisions regarding acquisition and dismission of resources (i.e. type and number of machines, transporters, load/unload stations, pallets) taken in each stage of the decision tree. Moreover, in each stage and for each workpiece a process plan is selected and its operations are assigned to the machine types. The configuration of the system before these decisions is determined by the decisions taken in the previous stage.

In this model there is a one-to-one correspondence among nodes in the scenario tree and in the decision tree (Fig. 7.7). The decisions are taken to cope with the outcomes modeled by the associated node of the scenario tree.

7.6.1 Notation and Parameters

The sets of elements that are necessary to model the problem together with their notation are reported in Table 7.1. Each set has already been defined in Chap. 4: Scenario Node (Table 4.3), Machine Type (Table 4.8), Workpiece Type (Table 4.1), Workingstep (Table 4.16), Workplan (Table 4.17) and Pallet Type (Table 4.18).

Table 7.1 Model notation

Index	Set
z	Scenario Node {1,.., Z}
i	Machine Type {1,..,I}
e	Workpiece Type{1,..,E}
w, $w1$, $w2$	Workingstep {1,..,W}
n	Workplan {1,..,N}
p	Pallet Type {1,..,P}

The Scenario Node set consists of all the nodes composing the scenario tree (Fig. 7.1). It is not necessary to introduce a set for modeling also the nodes of the decision tree thanks to the one-to-one correspondence among nodes in the two trees. Indeed, it is possible to refer to a node of the decision tree through the node of the scenario tree where these decisions take place. This assumption allows to simplify the formulation of the model.

The Machine Type set consists of all the types of machining centers that can be acquired or that are already available in the present system configuration.

The Workpiece Type set is composed of the part types that must be produced in the system to satisfy the demand. A workpiece type requires a set of operations to be produced and all these operations are the elements of the Workingstep set. Indeed, a workingstep (see Sect. 4.6) represents the machining process for a specific feature of the workpiece.

The Workplan set consists of all the alternative process plans that can be adopted to machine the considered workpiece types. A workplan is a collection of workingsteps with an execution sequence and in the context of this model it can also be seen as an ordered sequence of pallet types. The pallet types that are necessary to complete the workplans are the elements of the Pallet Type set.

The formulation of an FFMS design model requires to consider a wide range of input data that are shown in the following tables. Most of the data can be grouped into three areas, as anticipated in Sect. 7.4.2: product (Table 7.2), process (Table 7.3) and production system (Table 7.4) areas. The remaining data consist of the scenario tree modeling (Table 7.5) and of other generic parameters (Table 7.6).

The stochastic data of the problem consist of the demand of workpieces and of the capacity of the resources during the time periods.

Table 7.2 Product data

Parameter	Definition
$D_{e,z}$	Demand of workpieces of type e in scenario node z
$Ews_{e,w}$	Equal to 1 if workingstep w is associated with workpiece type e, 0 otherwise
$Ep_{e,p}$	Equal to 1 if pallets of type p are used to process workpieces of type e, 0 otherwise
mc_e	Penalty/outsourcing cost for one workpiece of type e

Table 7.3 Process data

Parameter	Definition
$m_{e,n}$	Equal to 1 if workplan *n* can be chosen to process workpieces of type *e*, 0 otherwise
vc	Cost of workplan validation and refinement
$Wp_{n,p}$	Equal to 1 if workplan *n* requires a pallet of type *p*, 0 otherwise
$Pws_{p,w}$	Equal to 1 if workingstep *w* can be processed on a pallet of type *p*, 0 otherwise
$Pm_{p,i}$	Equal to 1 if pallets of type p can be loaded on machines of type *i*, 0 otherwise
$PwsM_{p,w,i}$	Equal to 1 if workingstep *w* can be processed on a pallet of type *p* when it is loaded on a machine of type *i*, 0 otherwise
$same_{w1,w2}$	Equal to 1 if workingstep *w1* and *w2* must be processed on the same pallet and on the same machine because of tolerance constraints, 0 otherwise
$time_{p,w,i}$	Mean machining time required by machines of type *i* to process workingstep *w* when its workpiece is mounted on a pallet of type *p*. This time takes into account cutting time, rapid movement time and tool change time
$\mathrm{Nws}_{\mathrm{p,w}}$	Number of parts on which the workingstep *w* can be processed when they are mounted on a pallet of type *p*
$Nparts_p$	Number of parts mounted on a pallet of type *p*
Nf_p	Number of different types of setup face on pallets of type *p*
we_p	Workpiece type which is mounted on pallets of type *p*

Table 7.4 System and resource data

Parameter	Definition
$N0_i$	Number of machines of type *i* already present in the initial system configuration
$Mm_{i,z}$	Time capacity of machines of type *i* in the planning period associated with scenario node *z*
Cm_i	Investment cost of a machine of type *i*
Cmd_i	Residual value of a machine of type *i*
tcp_i	Time to change a pallet on a machine of type *i*
α_i^m	Maintenance coefficient of machines of type *i*
$Q0$	Number of carriers already present in the initial system configuration
Mt_z	Time capacity of the carriers in the planning period associated with scenario node *z*
Ct	Investment cost of carriers
Ctd	Residual value of carriers
tt	Mean transport time for a mission of the carrier
α^t	Maintenance coefficient of carriers
δ	Availability coefficient of carriers
$S0$	Number of load/unload stations already present in the initial system configuration
Ml_z	Time capacity of a load/unload station in the planning period associated with scenario node *z*
Cl	Investment cost of load/unload stations
Cld	Residual value of load/unload stations
α^l	Maintenance coefficient of load/unload stations
$T0_p$	Number of pallets of type *p* already present in the initial system configuration
$Mp_{p,z}$	Time capacity of pallets of type *p* in the planning period associated with scenario node *z*
Cp_p	Investment cost for pallets of type *p*

Table 7.4 (continued)

Parameter	Definition
Cpd_p	Residual value of pallets of type p
tlu_p	Total time required to load/unload all the workpieces on/from a pallet of type p
σ	Coefficient which estimates the average increase of the system time of a pallet given the presence of queues
γ	Planning coefficient that reduces the availability of the resources due to human factors

Table 7.5 Scenario data

Parameter	Definition
pr_z	Realization probability associated with scenario node z
st_z	Stage of scenario node z $\{1, 2, 3, \ldots.\}$
par_z	Parent node of scenario node z

Table 7.6 Model data

Parameter	Definition
η	Scrap coefficient
r	Discount rate
L	High value constant

7.6.2 Decision Variables

According to the multi-stage stochastic programming approach (see Sect. 7.4.1), the decision variables are associated with the nodes belonging to the different time stages. It means that in addition to the decisions taken at the beginning of the planning horizon (i.e. the initial system configuration), it is possible to take additional decisions in subsequent stages (i.e. system reconfigurations).

The set of decision variables can be divided into three groups as shown in the following tables. The decision variables related to the cost of the system and the shortfall production are reported in Table 7.7. The decision variables regarding

Table 7.7 Cost and shortfall production related decision variables

Variable	Definition
$COST_z \in \mathbb{R}$	Cost of the system associated with scenario node z
$MissW_{p,w,i,z}$	Shortfall volume of workingstep w when it should be processed on pallets of type p, loaded on machines of type i in the planning period associated with scenario node z
$MissP_{p,z} \in \mathbb{N}$	Shortfall volume of pallets of type p in the planning period associated with scenario node z
$Miss_{e,z} \in \mathbb{N}$	Shortfall/outsourcing volume of workpieces of type e in the planning period associated with scenario node z

Table 7.8 Process related decision variables

Variable	Definition
$x_{p,i,z} \in \{0,1\}$	Equal to 1 if pallets of type p must be processed by machines of type i in the planning period associated with scenario node z, 0 otherwise
$wpl_{n,z} \in \{0,1\}$	Equal to 1 if workplan n is selected to be processed in the system in the planning period associated with scenario node z, 0 otherwise
$new_{n,z} \in \{0,1\}$	Equal to 1 if workplan n must be validated before the beginning of the planning period associated with scenario node z, 0 otherwise
$xpal_{p,z} \in \{0,1\}$	Equal to 1 if pallets of type p must be processed in the system in the planning period associated with scenario node z, 0 otherwise
$y_{p,w,i,z} \in \{0,1\}$	Equal to 1 if workingstep w is processed on pallets of type p when they are loaded on machines of type i in the planning period associated with scenario node z, 0 otherwise

the process planning are listed in Table 7.8. Finally, the decision variable defining the set of resources in the manufacturing system during the planning horizon are listed in Table 7.9.

Table 7.9 Resource related decision variables

Variable	Definition
$N_{i,z} \in \mathbb{N}$	Total number of machines of type i in the system in the planning period associated with scenario node z
$S_z \in \mathbb{N}$	Total number of load/unload stations in the system in the planning period associated with scenario node z
$Q_z \in \mathbb{N}$	Total number of carriers in the system in the planning period associated with scenario node z
$T_{p,z} \in \mathbb{N}$	Total number of pallets of type p in the system in the planning period associated with scenario node z
$NP_{i,z} \in \mathbb{N}$	Number of machines of type i acquired before the beginning of the planning period associated with scenario node z
$SP_z \in \mathbb{N}$	Number of load/unload stations acquired before the beginning of the planning period associated with scenario node z
$QP_z \in \mathbb{N}$	Number of carriers acquired before the beginning of the planning period associated with scenario node z
$TP_{p,z} \in \mathbb{N}$	Number of pallets of type p acquired before the beginning of the planning period associated with scenario node z
$NM_{i,z} \in \mathbb{N}$	Number of machines of type i dismissed before the beginning of the planning period associated with scenario node z
$SM_z \in \mathbb{N}$	Number of load/unload stations dismissed before the beginning of the planning period associated with scenario node z
$QM_z \in \mathbb{N}$	Number of carriers dismissed before the beginning of the planning period associated with scenario node z
$TM_{p,z} \in \mathbb{N}$	Number of pallets of type p dismissed before the beginning of the planning period associated with scenario node z

7.6.3 Objective Function and Constraints

The objective function (7.1) of the model aims at minimizing the expected cost of the manufacturing system during the planning horizon considering all the stochastic data. This expected cost depends on the cost associated with each scenario node ($COST_z$) which is weighted according to the realization probability of the scenario node z and the discount rate r.

$$\min \sum_{z=1}^{Z} \frac{COST_z \cdot pr_z}{(1+r)^{st_z-1}} \tag{7.1}$$

Constraint (7.2) defines how the cost associated with each scenario node z is calculated. The cost consists of the investment cost to acquire the resources; this cost is reduced if some resources are sold. Moreover, the cost is increased when the manufacturing system cannot meet the demand thus incurring in penalty or outsourcing costs. The last term of the cost function takes into account the cost related to the validation of new workplans.

$$\begin{aligned} COST_z = & \left\{ \sum_{i=1}^{I} Cm_i NP_{i,z} + Ct \cdot QP_z + Cl \cdot SP_z + \sum_{p=1}^{P} Cp_p TP_{p,z} \right\} + \\ & - \left\{ \sum_{i=1}^{I} Cmd_i NM_{i,z} + Ctd \cdot QM_z + Cld \cdot SM_z + \sum_{p=1}^{P} Cpd_p TM_{p,z} \right\} + \\ & + \sum_{e=1}^{E} mc_e \cdot MISS_{e,z} + \sum_{n=1}^{N} vc \cdot new_{n,z}, \quad \forall z \end{aligned} \tag{7.2}$$

The constraints of the model have been formulated to cope with the issues of the FFMS design approach presented in Sect. 7.4. The constraints are divided into three groups: Process, Functionality and Capacity constraints. This partition is coherent with what Terkaj et al. (2008) have suggested about the design of systems embedding flexibility. Indeed, Process, Functionality, Capacity and Production Planning Flexibility are basic flexibility dimensions (see Sect. 3.1.4) that lead to the definition of the constraints matching the requirements of the production problem with the selectable resources.

According to the multi-stage stochastic programming approach, all the constraints of the model are replicated for each scenario node z composing the scenario tree.

The group of Process constraints consists of expressions (7.3), (7.4), (7.5), (7.6), (7.7) and (7.8). These constraints deal with the selection of the process plans for all the workpiece types and the satisfaction of tolerance constraints:

$$\sum_{n=1}^{N} wpl_{n,z} \cdot m_{e,n} = 1, \quad \forall e, z \tag{7.3}$$

$$xpal_{p,z} = \sum_{n} wpl_{n,z} \cdot Wp_{n,p}, \quad \forall p, z \tag{7.4}$$

$$new_{n,z} = wpl_{n,z}, \quad \forall n, z : st_z = 1 \tag{7.5}$$

$$new_{n,z} \geq wpl_{n,z} - wpl_{n,par(z)}, \quad \forall n, z : st_z \geq 2 \tag{7.6}$$

$$new_{n,z} \geq y_{i,w,p,z} - y_{i,w,p,par(z)}, \quad \forall p, w, i, n : Wp_{n,p} = 1, PwsM_{p,w,i} = 1; \forall z : st_z \geq 2 \tag{7.7}$$

$$\left(y_{p,w1,i,z} - y_{p,w2,i,z}\right) same_{w1,w2} = 0, \quad \forall p, i, z, w1, w2 : w1 \neq w2 \tag{7.8}$$

One workplan is selected for each workpiece type in each node z (7.3). The choice of the workplan leads to the definition of the pallet types that must be processed in the system (7.4). As said before, when a new workplan is chosen it is necessary to validate it (7.5) and (7.6), in order to check if the process plan is able to yield products with the required precision. This validation is necessary also when one or more workingstep assignments to the machines are changed (7.7). Finally, also tolerance constraints must be satisfied; since a pallet type can be assigned to more than one machine type thus splitting its related workingsteps, it is necessary to guarantee that critical operations are executed not only on the same pallet, but also on the same machine (7.8).

The group of Functionality constraints consists of expressions (7.9), (7.10), (7.11), (7.12) and (7.13) and defines how the process plans are implemented in the manufacturing system:

$$\sum_{i} x_{p,i,z} \cdot Pm_{p,i} \geq xpal_{p,z}, \quad \forall p, z \tag{7.9}$$

$$\sum_{i} x_{p,i,z} \leq xpal_{p,z} \cdot L, \quad \forall p, z \tag{7.10}$$

$$\sum_{w} y_{p,w,i,z} \leq x_{p,i,z} \cdot Pm_{p,i} \cdot L, \quad \forall p, i, z \tag{7.11}$$

$$\sum_{i} y_{p,w,i,z} = xpal_{p,z} \cdot Pws_{p,w}, \quad \forall w, p, z \tag{7.12}$$

$$y_{p,w,i,z} \leq PwsM_{p,w,i}, \quad \forall p, w, i, z \tag{7.13}$$

The pallet types that are required to complete the selected workplans must be assigned to at least one machine type in each scenario node z (7.9), checking if the pallet can be loaded on the machine (i.e. when $Pm_{p,i} = 1$). If a pallet type is not required by any workplan, then it must not be assigned to any machine type (7.10).

After a pallet type has been assigned to a set of machine types, each workingstep associated with that pallet type must be assigned to only one machine type (7.12). This assignment is possible only if the selected machine type can execute the workingstep (7.13), i.e. when $PwsM_{p,w,i} = 1$.

The group of Capacity constraints consists of expressions (7.14), (7.15), (7.16), (7.17), (7.18), (7.19), (7.20), (7.21), (7.22), (7.23), (7.24), (7.25), (7.26) and (7.27) and deals with the definition of the types and number of resources in each scenario node. Moreover, these constraints calculate the consumption of resource capacity and shortfall volumes:

$$N_{i,z} = NP_{i,z} + N0_i, \quad \forall i, z : st_z = 1 \tag{7.14}$$

$$Q_z = QP_z + Q0, \quad \forall z : st_z = 1 \tag{7.15}$$

$$S_z = SP_z + S0, \quad \forall z : st_z = 1 \tag{7.16}$$

$$T_{p,z} = TP_{p,z} + T0_p, \quad \forall p, z : st_z = 1 \tag{7.17}$$

$$N_{i,z} = N_{i,par(z)} + NP_{i,z} - NM_{i,z}, \quad \forall i, z : st_z \geq 2 \tag{7.18}$$

$$Q_z = Q_{par(z)} + QP_z - QM_z, \quad \forall z : st_z \geq 2 \tag{7.19}$$

$$S_z = S_{par(z)} + SP_z - SM_z, \quad \forall z : st_z \geq 2 \tag{7.20}$$

$$T_{p,z} = T_{p,par(z)} + TP_{p,z} - TM_{p,z}, \quad \forall p, z : st_z \geq 2 \tag{7.21}$$

$$\begin{aligned} &\sum_{p=1}^{P} \sum_{w=1}^{W} time_{p,w,i} \left(\frac{Nf_p \cdot D_{we_p,z} \cdot Nws_{p,w}}{Nparts_p} y_{p,w,i,z} - MissW_{p,w,i,z} \right) + \\ &+ \sum_{p=1}^{P} tcp_i \left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} x_{p,i,z} - MissP_{p,z} \right) \leq \eta \alpha_i^m \gamma \cdot Mm_{i,z} \cdot N_{i,z}, \quad \forall i, z \end{aligned} \tag{7.22}$$

$$\begin{aligned} &\sum_{p=1}^{P} \sum_{i=1}^{I} \left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} x_{p,i,z} - MissP_{p,z} \right) + \\ &+ \sum_{p=1}^{P} \left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} xpal_{p,z} - MissP_{p,z} \right) \leq \frac{\eta \delta \alpha^t \gamma \cdot Mt_z \cdot Q_z}{tt}, \quad \forall z \end{aligned} \tag{7.23}$$

$$\sum_{p=1}^{P} 2tlu_p \left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} xpal_{p,z} - MissP_{p,z} \right) \leq \eta \alpha^l \gamma \cdot Ml_z \cdot S_z, \quad \forall z \tag{7.24}$$

$$\sum_{i=1}^{I}\sum_{w=1}^{W} time_{p,w,i}\left(\frac{Nf_p \cdot D_{we_p,z} \cdot Nws_{p,w}}{Nparts_p} y_{p,w,i,z} - MissW_{p,w,i,z}\right)+$$
$$+\left(tt + 2 \cdot tlu_p\right)\left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} xpal_{p,z} - MissP_{p,z}\right)+ \quad (7.25)$$
$$+\sum_{i=1}^{I}(tt + tcp_i)\left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} x_{p,i,z} - MissP_{p,z}\right) \le \eta\sigma \cdot Mp_{p,z} \cdot T_{p,z}, \quad \forall p, z$$

$$MISS_{e,z} \ge Ews_{e,w} \cdot \sum_{p=1}^{P}\sum_{i=1}^{I} MissW_{p,w,i,z}, \quad \forall e, w, z \quad (7.26)$$

$$MISS_{e,z} \ge MissP_{p,z} \cdot Nparts_p \cdot Ep_{e,p}, \quad \forall e, p, z \quad (7.27)$$

Constraints (7.14), (7.15), (7.16), (7.17), (7.18), (7.19), (7.20) and (7.21) define the number of resources that are available in the system at each scenario node z. The constraints are replicated for each resource type, i.e machine, carrier, load/unload station and pallet.

In the root node (7.14), (7.15), (7.16) and (7.17) the total number of resources ($N_{i,z}$, Q_z, S_z, $T_{p,z}$) is equal to the number of devices already available in the system ($N0_i$, $Q0$, $S0$, $T0_p$) plus the purchased devices ($NP_{i,z}$, QP_z, SP_z, $TP_{p,z}$) minus the sold devices ($NM_{i,z}$, QM_z, SM_z, $TM_{p,z}$). If system design starts from green field, then there are no devices already available in the system (i.e. $N0_i$, $Q0$, $S0$, $T0_p$ are all equal to zero). In the stages which follow the first one (7.18), (7.19), (7.20) and (7.21), the parameters representing the number of devices already available in the system are replaced by the variables indicating the number of devices which are available in the parent node.

Constraints (7.22), (7.23), (7.24) and (7.25) model how the available capacity of the different resource types can be used to produce the workpieces. In these constraints the actual production volume is calculated as a difference between the demand and the shortfall/outsourcing volume.

Machine capacity (7.22) is dedicated both to cutting operations and to the movement of pallets. The first activity is related to the total number of workingsteps and to the time to execute a single workingstep ($time_{p,w,i}$), while the second activity is related to the number of loaded pallets and to the time required to change the pallet in the working position (tcp_i). The available capacity of machine type i in a given scenario node depends on the total number of machines of that type in the system ($N_{i,z}$) and on the time capacity of a single machine ($Mm_{i,z}$) during the planning period of the considered scenario node z. Anyway, this theoretical capacity is reduced by inefficiencies which are due to scraps, maintenance and production planning.

Carrier capacity (7.23) is used to transport pallets in the system. The considered missions are the following ones:

- from a load/unload station to a machine;
- from a machine to another machine;
- from a machine to a load/unload station.

With this assumption, each pallet type requires a number of missions that is equal to the number of machines that it has been assigned to plus one; this hypothesis is valid if a pallet does not visit the same machine more than once. The left-hand side of expression (7.23) models the total number of missions, while the right-hand side models the maximum number of missions that the carriers in the system can perform. This maximum number of missions depends on the number of carriers in the system (Q_z), on the time capacity (Mt_z) of a carrier during the time period of scenario node z and on the mean time required by each mission (tt). The theoretical capacity of the carriers is decreased by inefficiencies which are due to scraps, maintenance and production planning. Moreover, the real carrier availability is reduced because additional missions can be necessary to move the pallets to/from the buffers. These additional missions are taken into account reducing the actual capacity of the carrier by an availability coefficient (δ), since they cannot be precisely estimated because they depend on the dynamic behavior of the system.

Load/unload station capacity (7.24) is dedicated to load and unload workpieces on/from the pallets. The total capacity depends on the number of stations (S_z) and on the time capacity of each station (Ml_z) during the planning period of scenario node z. The theoretical capacity is reduced by inefficiencies which are due to scraps, maintenance and production planning.

The pallet capacity constraint (7.25) defines how many pallets of each type are necessary to satisfy the demand. The left-hand side of the constraint models the system time required by a pallet to be completely processed. The required time is spent for the following activities: loading of the workpieces, transportation to the various machines, machining of the workpieces, transportation to the load/unload station and finally unloading of the workpieces. The total capacity of each pallet type depends on the number of pallets of that type in the system ($T_{p,z}$) and on the time capacity of a single pallet (Ml_z) during the planning period of scenario node z. The theoretical capacity is reduced by inefficiencies which are due to scraps η and queues in the system σ.

If system capacity is not sufficient to satisfy the demand, then the shortfall/outsourcing volume of workpiece types can be calculated according to the shortfall of workingsteps (7.26) and pallets (7.27).

7.7 Total Cost Stochastic Model

The previous section has presented a multi-stage stochastic programming model to solve the problem of FFMS design. The model aims at identifying the type and number of devices to be purchased in order to face the production problems, while minimizing the system cost consisting of resource investment, shortfall/outsourcing production and process planning decisions. However, in order to develop a detailed analysis of the FFMSs profitability compared to other system architecture, a total cost analysis should be carried out. This modeling becomes crucial when system reconfigurations are required to face frequent production changes (Terkaj et al. 2008).

Reconfigurability and flexibility are two options that can be mixed in an FFMS on the basis of their costs. For instance, it is possible to acquire more flexibility then the amount strictly required by the present production problem in order to avoid possible future system reconfigurations and ramp-ups. Indeed, the system ramp-up phase represents a critical and less investigated issue. The production system ramp-up is defined in the literature as “the time interval it takes a newly introduced or just reconfigured production system to reach sustainable, long-term levels of production, in terms of throughput and part quality, considering the impact of equipment and labor on productivity” (Koren et al. 1999; Koren 2006). The ability to successfully ramp-up the production when new products are introduced and demand volumes change has become a critical issue for many manufacturing companies, especially for Original Equipment Manufacturers and their suppliers (Matta et al. 2008). Therefore, manufacturers need to manage production ramp-ups both in a time-efficient and in a cost-efficient manner. Many factors impacting on the system ramp-up have been identified and the most influencing ones seem to be related to the learning process (Li and Rajagopalan 1998; Terwiesch and Bohn 2001; Hatch and Macher 2004).

Despite the importance of system ramp-up is deeply perceived by companies, it seldom happens that the manufacturing system designer quantitatively considers the phenomenon when configuring new systems or reconfiguring existing ones. It is difficult to precisely evaluate the ramp-up time and cost because they depend on the heterogeneous factors which are involved. However, the analysis of the issues related to the system ramp-up phase supports the idea that neglecting the existence of ramp-ups in the reconfiguration problem can lead to make mistakes in determining the required system capacity and to underestimate the costs related to penalties both for lost production and system inefficiencies (Matta et al. 2008). The main feature of a system ramp-up is the non-steady-state production, due to the system inability to reach its full production potential because of higher frequency of machine/system breakdowns, higher percentage of scrap or reworks and poor understanding of the best way to operate the system in its new configuration.

It is possible to consider the case of a production system that has to be designed to cope with a certain demand level and after a period of time it should be reconfigured in order to cope with a new demand level. Figure 7.9 illustrates the production throughput function of the production system introduced in this example. In this case, the present and forecasted production requirements lead the system designer to handle a two-stage decision process. In the first stage the production system has to be designed in order to guarantee a throughput Th_1. However, the production system requires a ramp-up period $[0;\tau_1)$ before reaching the objective production rate; this period will be followed by a steady-state period $[\tau_1;Tss_1)$. The ramp-up period is characterized by an insufficient number of processed parts and a growing throughput rate. For the

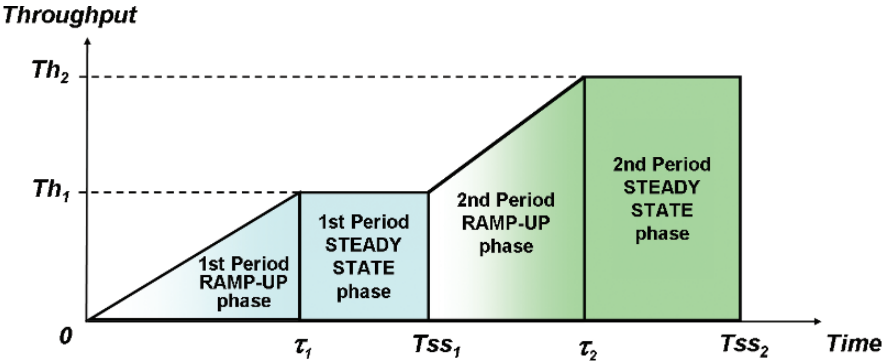


Fig. 7.9 Representation of the production system ramp-up and steady-state phase

sake of simplicity, this phenomenon is represented as a linear ramp in the figure and the steady-state period is characterized by the production of a constant rate of parts. As anticipated, a new level of demand must be satisfied by the system after the end of the first time period. The increased demand forces the decision maker to design a system reconfiguration in which new resources are installed to achieve the throughput level Th_2. This means to face a second period composed of a ramp-up and a steady-state phase characterized by the intervals [Tss_1; τ_2) and [τ_2; Tss_2) respectively.

During the ramp-up period, the production system does not reach the target production level. This impacts both on operating and maintenance costs. For instance, penalties related to the lost production as well as intensive maintenance activity related to the higher probability of machine failures and malfunctioning must be considered. Moreover, during the ramp-up phase the purchased resources tend to be used inefficiently thus leading to higher operating costs.

7.7.1 Basic Assumptions

The model presented in this section has been developed assuming that the designed manufacturing system must be able to cope with the demand and its forecasted evolution. This means to consider the outsourcing option if the production system does not satisfy the demand. The model does not consider holding costs, i.e. the possibility to keep and maintain a stock of goods in storage.

The design model considers the following costs in addition to the investement and outsourcing/shortfall costs (see Sect. 7.6):

- Operating costs (related to the production of all the required parts);
- Maintenance costs.

Each type of cost has been considered during both the ramp-up and the steady state phases. Other assumptions concern the profile of the system throughput function as it is represented in Fig. 7.9. Firstly, the throughput function linearly increases with time until it reaches the steady state value. Secondly, it is assumed that the duration of the ramp-up phase never exceeds the length of the whole period.

Concerning the machine reliability, resource failure and repair rates have already been estimated. The failure rate is related to the resource type.

The Total Cost model has been formulated as an extension of the basic FFMS design model presented in Sect. 7.6. Therefore all the parameters (see Sect. 7.6.1), decision variables (see Sect. 7.6.2) and constraints (see Sect. 7.6.3) of the basic model are still valid, except where specified. The additional characteristics of the Total Cost model are defined in the following sub-sections.

7.7.2 Notation and Parameters

This section provides the set of new parameters included in the Total Cost model beyond those already defined in Tables 7.2, 7.3, 7.4, 7.5 and 7.6. These additional parameters define the characteristics of the planning horizon and ramp-up phase (Table 7.10), the failure rates (Table 7.11) and the production and maintenance costs (Table 7.12).

Table 7.10 Planning horizon and ramp-up parameters

Parameter	Definition
τ_z	End of system ramp-up phase in the planning period associated with scenario node z
Tss_z	End of system steady state period in the planning period associated with scenario node z
$coeffRU_z$	Coefficient that reduces the capacity of the new resources during the ramp-up phase in the period associated with scenario node z

Table 7.11 Failure parameters

Parameter	Definition
$MTBF_{RUi}$	Mean time between failures of machines of type i during the rump-up phase
$MTBFt_{RU}$	Mean time between failures of carriers during the rump-up phase
$MTBFl_{RU}$	Mean time between failures of load/unload stations during the rump-up phase
$MTBF_i$	Mean time between failures of machines of type i during the steady state phase
$MTBFt$	Mean time between failures of carriers during the steady state phase
$MTBFl$	Mean time between failures of load/unload stations during the steady state phase

Table 7.12 Production and maintenance cost parameters

Parameter	Definition
λ_{pRU}	Production cost during the rump-up phase [cost/pallet]
λ_p	Production cost during the steady state phase [cost/pallet]
$CFprod_z$	Fixed production costs in the planning period associated with scenario node z
$CFmant_z$	Fixed maintenance costs in the planning period associated with scenario node z
λm_i	Maintenance cost of machines of type i during the ramp-up and steady-state phases [cost/machine]
λmt	Maintenance cost of carriers during the ramp-up and steady-state phases [cost/carrier]
λml	Maintenance cost of load/unload stations during the ramp-up and steady-state phases [cost/load-unload station]
λm_p	Maintenance cost of pallets of type p [cost/pallet]

7.7.3 Decision Variables

The decision variables of the basic FFMS design model have already been introduced in Sect. 7.6.2 (Tables 7.7, 7.8 and 7.9). The additional decision variables modeling the different costs of the system and the number of processed pallets are reported in Table 7.13.

7.7.4 Objective Function and Constraints

The Total Cost model is formulated as a multi-stage stochastic programming model. In this sub-section the objective function and the constraints of the model are presented and explained. Constraints (7.2), (7.3), (7.4), (7.5), (7.6), (7.7), (7.8), (7.9), (7.10), (7.11), (7.12), (7.13), (7.14), (7.15), (7.16), (7.17), (7.18), (7.19), (7.20) and (7.21) and (7.26), (7.27) defined in Sect. 7.6.3 for the basic model are still valid in the Total Cost extension.

The new objective function (7.28) substitutes (7.1) and it aims at minimizing the expected total cost during the planning horizon.

$$\min \text{cost} = \sum_{z=1}^{Z} \frac{TC_z \cdot pr_z}{(1+r)^{st_z - 1}} \tag{7.28}$$

Table 7.13 Additional decision variables of the Total Cost model

Variable	Definition
$TC_z \in \mathbb{R}$	Total cost in the planning period associated with scenario node z
$OP_z \in \mathbb{R}$	Production cost in the planning period associated with scenario node z
$MANT_z \in \mathbb{R}$	Maintenance cost in the planning period associated with scenario node z
$V_{p,z} \in \mathbb{R}$	Production volume of pallets of type p in the planning period associated with scenario node z

As previously stated, the total cost includes the investment costs ($COST_z$), the operating costs (OP_z) and the maintenance costs ($MANT_z$). The components of the total cost function are defined in constraint (7.29).

$$\mathrm{TC_z} = \mathrm{COST_z} + OP_\mathrm{z} + MANT_\mathrm{z}, \quad \forall z \tag{7.29}$$

$$OP_\mathrm{z} = CFprod_z + \sum_{p=1}^{P} \lambda_p \left(Tss_z - Tss_{par_z} \right) V_{p,z}, \quad \forall z : V_{p,z} \le V_{p,par_z} \tag{7.30}$$

$$\begin{aligned} OP_\mathrm{z} =& CFprod_z + \sum_{p=1}^{P} \frac{\lambda_{pRU}}{2} \left(\tau_z - Tss_{par_z)} \right) \left(V_{p,z} - V_{p,par_z} \right) + \\ &+ \sum_{p=1}^{P} \lambda_p \left(Tss_z - \tau_z \right) V_{p,z}, \quad \forall z : V_{p,z} > V_{p,par_z} \end{aligned} \tag{7.31}$$

$$\begin{aligned} MANT_\mathrm{z} = CFmant_z + \sum_{p=1}^{P} \lambda m_p \cdot T_{p,z} + \\ + \left(Tss_z - Tss_{par_z} \right) \left\{ \sum_{i=1}^{I} \tfrac{\lambda m_i}{MTBF_i} N_{i,z} + \tfrac{\lambda mt}{MTBFt} Q_z + \tfrac{\lambda ml}{MTBFl} S_z \right\} + \\ + \left(\tau_z - Tss_{par_z} \right) \left\{ \sum_{i=1}^{I} \left(\tfrac{1}{MTBF_{RUi}} - \tfrac{1}{MTBF_i} \right) \lambda m_i NP_{i,z_z} + \right. \\ \left. + \left(\tfrac{1}{MTBFt_{RU}} - \tfrac{1}{MTBFt} \right) \lambda mt \cdot QP_z + \left(\tfrac{1}{MTBFl_{RU}} - \tfrac{1}{MTBFl} \right) \lambda ml \cdot SP_z \right\}, \forall i, z, p \end{aligned} \tag{7.32}$$

The variable $COST_z$ takes into account investment costs, process planning costs and outsourcing/shortfall costs. These costs have already been defined in constraint (7.2) within Sect. 7.6.3.

Production costs are defined by constraints (7.30) and (7.31). Constraint (7.30) determines the cost related to process the demanded quantity of pallets when the system does not face a ramp-up. This cost is composed of a constant value and a variable one. The constant value includes fixed costs which are due, for instance, to the rental of buildings. The variable part of the cost depends on the volume of manufactured pallets and it is related, for instance, to the cost of energy required by the resources, labor costs and the cost of raw materials. When production volumes grow from a period to the next one, constraint (7.31) allows to calculate the production costs considering also the ramp-up phase; during this phase the production costs can be higher because of non-optimal settings of the process parameters.

Constraints (7.32) models the maintenance costs which consist of four terms:

1. a fixed maintenance cost ($CFmant_z$) allocated by the firm for the ordinary maintenance activities;
2. a cost associated with pallet maintenance;

3. a cost required to maintain the total number of devices installed in each system configuration during the period associated with scenario node z;
4. an additional maintenance costs related to the ramp-up period during which possible resource breakdowns or malfunctioning can occur with a higher frequency.

Constraint (7.33) defines the total number of processed pallet in the planning period associated with scenario node z, given by the requested volume minus the shortfall volume.

$$V_{p,z} = \left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} xpal_{p,z} - MissP_{p,z} \right), \quad \forall p, z \tag{7.33}$$

Constraints (7.34), (7.35), (7.36) and (7.37) substitute the capacity constraints (7.22), (7.23), (7.24) and (7.25) of the basic FFMS design model to calculate the capacity of the different resource types: machines (7.34), carriers (7.35), load/unload stations (7.36) and pallets (7.37).

The new constraints are similar to the previous ones and most of the terms have the same meaning. The capacity of the new resources which have been purchased to face production changes is reduced during the ramp-up phase by a coefficient $coeffRU_z$. Indeed, the real availability of the resources is limited by the learning processes when new devices are installed in the system. Therefore, a new resource will not be able to immediately achieve its full capacity because of the ramp-up.

The coefficient of capacity reduction of new resources (i.e. $coeffRU_z$) has been assumed to be the same for machines, carriers, load/unload stations and pallets. Also, a new resource facing a ramp-up could influence the other resources already present in the system. The level of interaction could be related to the type of resource which has been purchased. Herein, for the sake of simplicity, it is assumed that the ramp-up phenomenon which affects a new resource does not affect the other resources already installed in the system.

$$\begin{aligned} &\sum_{p=1}^{P} \sum_{w=1}^{W} time_{p,w,i} \left(\frac{Nf_p \cdot D_{we_p,z} \cdot Nws_{p,w}}{Nparts_p} y_{p,w,i,z} - MissW_{w,z} \right) + \\ &\quad + \sum_{p=1}^{P} tcp_i \left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} x_{p,i,z} - MissP_{p,z} \right) \leq \\ &\quad \leq \eta \alpha_i^m \gamma \cdot Mm_{i,z} \cdot \left(N_{i,z} - coeffRU_z \cdot NP_{i,z} \right), \quad \forall i, z \end{aligned} \tag{7.34}$$

$$\begin{aligned} &\sum_{p=1}^{P} \sum_{i=1}^{I} \left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} x_{p,i,z} - MissP_{p,z} \right) + \sum_{p=1}^{P} \left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} xpal_{p,z} - MissP_{p,z} \right) \leq \\ &\quad \leq \frac{\eta \delta \alpha^t \gamma \cdot Mt_z \cdot (Q_z - coeffRU_z \cdot QP_z)}{tt}, \quad \forall z \end{aligned} \tag{7.35}$$

$$\sum_{p=1}^{P} 2tlu_p \left(\frac{Nf_p D_{we_p,z}}{Nparts_p} xpal_{p,z} - MissP_{p,z} \right) \leq \\ \leq \eta \alpha^l \gamma \cdot Ml_z \cdot (S_z - coeffRU_z \cdot SP_z), \quad \forall z \tag{7.36}$$

$$\sum_{w=1}^{W} time_{p,w,i} \left(\frac{Nf_p \cdot D_{we_p,z} \cdot Nws_{p,w}}{Nparts_p} y_{p,w,i,z} - MissW_{w,z} \right) + \\ + \left(tt + 2 \cdot tlu_p \right) \left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} xpal_{p,z} - MissP_{p,z} \right) + \\ + \sum_{i=1}^{I} (tt + tcp_i) \left(\frac{Nf_p \cdot D_{we_p,z}}{Nparts_p} x_{p,i,z} - MissP_{p,z} \right) \leq \\ \leq \eta \sigma \cdot Mp_{p,z} \cdot \left(T_{p,z} - coeffRU_z \cdot TP_{p,z} \right), \ c \quad \forall p, z \tag{7.37}$$

7.8 Bid Generation Model

As introduced in Chap. 1, the problem of system design can be addressed both by machine tool builders and by system users. In this chapter the design activity is carried out by the machine tool builder who identifies a set of alternative system configurations that fit the production requirements with different levels of efficiency and cost-effectiveness. As introduced in Sect. 7.5, the design model presented in this section focuses the attention on the objective function of the machine tool builder. The final goal of the machine tool builder is the maximization of his expected profit and not the minimization of the system cost, even if these two objectives are related. At first, the machine tool builder can identify a set of alternative manufacturing system configurations fitting the production requirements with the minimum economic efforts. Afterwards, starting from the optimal solution he could evaluate how to generate the economic bid aiming at maximizing his expected profit.

The works addressing the bid generation problem for a generic seller are typically economics-oriented and study the interaction between seller and buyer defining mathematical utility functions (Talluri 2002; Che and Gale 2000). These approaches are not easy to apply because complex knowledge and elaborations of the decision makers cannot be fully represented by utility functions. To solve this problem Chapman et al. (2000) developed a framework supporting the generation of competitive bids in uncertain environments.

The objective of the bid generation model is the maximization of the utility of the machine tool builder, finding the optimal trade-off between profitability and probability of winning the order. The difference between the knowledge and the objectives of the machine tool builder and the system user can lead to manufacturing systems configurations which are suboptimal from the point of view of the system user. This situation can happen in various situations, e.g. when the machine tool builder designs a system with excessive flexibility due to incomplete information received from the system user or when the machine tool builder succeeds in selling an oversized system. Since the point of view of the machine tool builder is adopted, several uncertain issues must be faced while addressing the problem:

- the evolution of the part mix and the capacity required by the manufacturing system;
- the available capacity in the plant of the machine tool builder is uncertain because the success rate of the present and future bids is unknown;
- the financial situation of the client (e.g. budget constraints) and the role of the client in his market;
- the technical characteristics and the economic value of the system solutions offered by the competitors of the machine tool builder.

To reduce the risk related to the bidding decisions, a tool based on multi-stage stochastic programming is presented to support the machine tool builder in generating a bid. One of the goals of the Bid Generation model is the quantitative study of how the decisions can impact on the profitability of the firm; the focus is on control parameters such as the markup percentage and the due date of the designed system capacity.

7.8.1 Notation and Parameters

The Bid Generation model can be considered as an extension of the basic FFMS design model described in Sect. 7.6 (Tables 7.1, 7.2, 7.3, 7.4, 7.5, 7.6, 7.7, 7.8 and 7.9). Therefore the production requirements of the potential client are still modeled by the scenario tree presented in Fig. 7.1. The additional sets that are necessary for the formulation of the model are shown in Table 7.14.

A new set has been introduced to model the different markup levels that a machine tool builder can select. The choice of the machine tool builder is influenced by many factors, e.g. its present financial situation, the saturation of its plant, the importance and the financial situation of the potential client.

Since the results of the bid depends on the market context where the machine tool builder plays, another set has been created to model the various market situations that the machine tool builder could face.

Table 7.14 Model notation

Index	Set
h	Market Situation {1,..,H}
j	Markup Level {1,..,J}
k	Time Stage {1,..,K}

Table 7.15 Model parameters

Parameter	Definition
ml_j	Markup percentage corresponding to the markup level j
fml	Mean markup percentage which is applicable when selling resources needed for system reconfigurations
spr_h	Realization probability of market situation h
$sr_{h,j}$	Success rate when markup level j is applied in market situation h
ov_k	Maximum oversizing of the designed system capacity in time stage k
$budg$	Client budget which is available for the initial system configuration
L	High value constant

The parameters of the basic model (Tables 7.2, 7.3, 7.4, 7.5 and 7.6) are integrated with new parameters reported in Table 7.15. These new parameters characterize the markup levels, the market situations, the oversizing of the manufacturing system and the budget of the potential client.

7.8.2 Decision Variables

The decision variables of the bid generation model are shown in Table 7.16. These variables are added to the set already defined in Sect. 7.6.2 (Tables 7.7, 7.8 and 7.9) to model the economic decisions.

7.8.3 Objective Function and Constraints

The Bid Generation model aims at maximizing the profit of the machine tool builder. However, when dealing with the maximization of the profit it is necessary to introduce the aspect of success rate of a commercial bid; indeed the profit is not certain since the client could prefer the bid prepared by a competitor.

Chapman et al. (2000) proposed a simple and plausible objective function maximizing the product of profit and success rate; the success rate linearly depends on the commercial bid and if the bid is increased, then the chance of winning the order decreases. This formulation is applied to cases where the

Table 7.16 Decision variables

Variable	Definition
$sel_j \in \{0,1\}$	Equal to 1 if markup level j has been selected
$B_j \in \mathbb{R}$	Commercial bid for the initial system configuration when markup level j is selected
$FB_z \in \mathbb{R}$	Commercial bid for the future system reconfiguration in scenario node z
$PROF_{j,z} \in \mathbb{R}$	Profit in scenario node z when markup level j is selected

technical bids proposed by the competitors are very close because the client has defined precise specifications (e.g. civil engineering facilities, health facilities, supply of services, etc.) thus leading to a "lowest price" competition. However, in the case of manufacturing system design, the technical bids of the machine tool builders can be very different.

Assuming that the system user can roughly evaluate the economic value of the alternative technological offers (i.e. system configurations) which are able to solve his production problem, the hypothesis can be made that the success rate of the bid depends on the difference between the commercial bid (i.e. the price of the system) and the economic value of the proposed system solution. This difference is equal to the markup and the machine tool builder can impact on his expected profit by choosing among different markup percentage levels (ml_j). However, the success rate associated with the markup levels cannot be deterministic because it depends also on external factors (i.e. market competition) which can be modeled by defining different market situations; each market situation has its realization probability. Therefore, the success rate of a bid ($sr_{h,j}$) depends both on the chosen markup level and on the market situation that will happen (herein, it is assumed that the market situation is not related to the characteristics of the scenario nodes evaluated by the machine tool builder).

The objective function of the model (7.38) aims at maximizing the expected profit of the machine tool builder. The profit ($PROF_{j,z}$) associated with each scenario node and markup level is weighted according to the realization probability of market situation h, the success rate of markup level j in market situation h and the realization probability of scenario node z.

$$\max \sum_{h=1}^{H} spr_h \sum_{j=1}^{J} sr_{h,j} \sum_{z=1}^{Z} pr_z \cdot PROF_{j,z} \tag{7.38}$$

All the constraints (7.2), (7.3), (7.4), (7.5), (7.6), (7.7), (7.8), (7.9), (7.10), (7.11), (7.12), (7.13), (7.14), (7.15), (7.16), (7.17), (7.18), (7.19), (7.20), (7.21), (7.22), (7.23), (7.24), (7.25), (7.26) and (7.27) defined for the basic FFMS design model formulation (see Sect. 7.6) are valid also for the bid generation model. Moreover, the constraints (7.39), (7.40), (7.41), (7.42), (7.43), (7.44) and (7.45) must be added to the model.

$$\sum_{j=1}^{J} sel_j \leq 1 \tag{7.39}$$

$$B_j \leq budg, \quad \forall j \tag{7.40}$$

$$B_j \leq \left(1 + ml_j\right) \cdot COST_z, \quad \forall j, z : st_z = 1 \tag{7.41}$$

$$PROF_{j,z} \leq B_j - COST_z, \quad \forall j, z : st_z = 1 \tag{7.42}$$

$$FB_z \leq (1 + fml) \cdot COST_z, \quad \forall z : st_z > 1 \tag{7.43}$$

$$PROF_{j,z} \leq FB_z - COST_z, \quad \forall j, z : st_z > 1 \tag{7.44}$$

$$PROF_{j,z} \leq sel_j \cdot L, \quad \forall j, z \tag{7.45}$$

Constraint (7.39) defines that no more than one markup level can be chosen to prepare the commercial bid. Constraint (7.40) imposes that the commercial bid cannot be higher than the budget of the client for any possible markup level.

The commercial bid (B_j) for each markup level j cannot exceed the system configuration cost by a quantity equal to the markup (7.41). Constraint (7.42) defines the profit ($PROF_{j,z}$) obtained by selling the initial system configuration for the first planning period which is associated with the root scenario node.

Constraints (7.41) and (7.42) are replaced by constraints (7.43) and (7.44) for the time stages following the first one. Constraint (7.43) defines the commercial bid related to future system reconfigurations, while constraint (7.44) defines the profit coming from these reconfigurations.

Constraint (7.45) imposes that if a markup level j is not selected (i.e. $sel_j = 0$), then the profit associated with that markup level must be equal to zero.

Since the goal of the machine tool builder is the maximization of his profit, there is the risk to design a system configuration that is highly oversized compared to the needs of the system user. Therefore a set of constraints (7.46), (7.47), (7.48) and (7.49) have been introduced to cope with this problem by limiting the system capacity.

$$\begin{aligned} \eta\alpha_i^m\gamma \cdot Mm_{i,z} \cdot N_{i,z} \leq (1 + ov_{st_z}) \sum_{p=1}^{P} tcp_i \left(\frac{Nf_p D_{we_p,z}}{Nparts_p} x_{p,i,z} - MissP_{p,z} \right) + \\ +(1 + ov_{st_z}) \sum_{p=1}^{P} \sum_{w=1}^{W} time_{p,w,i} \left(\frac{Nf_p D_{we_p,z} Nws_{p,w}}{Nparts_p} y_{p,w,i,z} - MissW_{w,z} \right), \forall i, z \end{aligned} \tag{7.46}$$

$$\begin{aligned} \frac{\eta\delta\alpha^t\gamma \cdot Mt_z \cdot Q_z}{tt} \leq (1 + ov_{st_z}) \sum_{p=1}^{P} \sum_{i=1}^{I} \left(\frac{Nf_p D_{we_p,z}}{Nparts_p} x_{p,i,z} - MissP_{p,z} \right) + \\ +(1 + ov_{st_z}) \sum_{p=1}^{P} \left(\frac{Nf_p D_{we_p,z}}{Nparts_p} xpal_{p,z} - MissP_{p,z} \right), \quad \forall z \end{aligned} \tag{7.47}$$

$$\eta\alpha^l\gamma \cdot Ml_z \cdot S_z \leq (1 + ov_{st_z}) \sum_{p=1}^{P} 2tlu_p \left(\frac{Nf_p D_{we_p,z}}{Nparts_p} xpal_{p,z} - MissP_{p,z} \right), \quad \forall z \tag{7.48}$$

$$\eta\sigma \cdot Mp_{p,z} \cdot T_{p,z} \leq (1 + ov_{st_z}) \sum_{i=1}^{I} (tt + tcp_i) \left(\frac{Nf_p D_{we_p,z}}{Nparts_p} x_{p,i,z} - MissP_{p,z} \right) + (1 + ov_{st_z}) \sum_{w=1}^{W} time_{p,w,i} \left(\frac{Nf_p D_{we_p,z} Nws_{p,w}}{Nparts_p} y_{p,w,i,z} - MissW_{w,z} \right) + +(1 + ov_{st_z}) \left(tt + 2 \cdot tlu_p \right) \left(\frac{Nf_p D_{we_p,z}}{Nparts_p} xpal_{p,z} - MissP_{p,z} \right), \quad \forall p, z \tag{7.49}$$

For each planning period associated with the different scenario nodes, the system capacity related to machines (7.45), carriers (7.46), load/unload stations (7.47) and pallets (7.48) cannot exceed the required capacity by a quantity equal to the maximum oversizing coefficient. The terms in constraints (7.45), (7.46), (7.47) and (7.48) have already been explained while describing the capacity constraints (7.22), (7.23), (7.24) and (7.25) of the basic FFMS design model (see Sect. 7.6.3).

7.9 Testing

The FFMS design model presented in Sect. 7.6 has been tested with the goal of investigating the benefits coming from the application of an FFMS design approach. As anticipated, the existence of a machine database composed of heterogeneous resources (in term of performance, architecture and costs) gives to the machine tool builder more options to customize the system flexibility on the production requirements.

The presence of many resource types offers the chance of designing different system configurations to solve the trade-off between flexibility and productivity. Indeed, previous works highlighted that the profitability of the FFMS solution is strongly influenced by the variety of machines composing the resource database (Tolio and Valente 2006, 2007). As stated in Chap. 1, FFMSs are hybrid systems, i.e. they can be composed of general purpose and dedicated machines. A general purpose machine is a traditional machining center that can execute a large set of operations thanks to its precision and flexibility. A dedicated machine is defined as a machine that is able to perform only a subset of all the operations that must be processed. For instance, dedicated machines can be drilling machines or roughing machines; another example of dedicated machine could be an old resource already available in the system, whose degraded performance allow to execute only a subset of operations.

Dedicated and general purpose machines differ not only in the set of performable operations but also in the investment cost. General purpose machines are intuitively more expensive than dedicated ones. The cost difference can arise from many aspects. For instance, a machine tool builder can operate on the machine architectures in terms of number of axes and working cube. Other key parameters influencing the machine cost are related to devices such as the spindle and the actuators that have an impact on machine performance and in particular on the cutting speed and rapid movement times for the various machining operations. For instance, a machining center dedicated to drilling operations must bear machining forces mainly along one working direction: this consideration enables to optimize the structure and the drives thus reducing the cost. More generally it may be possible to reduce the cost for devices and structural components, making at the same time the machine lighter and faster in rapid traverse movements. A further category is represented by machines whose investment cost reduction is compensated by a worse machine performance. A clear example is represented by old machines, including general purpose ones, which can be dedicated to perform few operations: even if their usage has reduced the precision of the machining process and the quality threshold cannot be satisfied for finishing operations, old machines can frequently be used for roughing operations. When a system configuration or reconfiguration is needed, old machines which are already available in the system can be kept in the new configuration or additional old machines can be purchased in the second-hand market at a lower price than state-of-the-art general purpose machining centers. Therefore, integrating this type of machines can give a competitive advantage to the FFMS solution.

The testing phase presented in this section is aimed at:

- evaluating the impact of an heterogeneous machine database on the system architecture;
- studying which are the types of production contexts where the cost reduction related to dedicated resources can be exploited at a system level, thus making an FFMS a winning solution compared to traditional Flexible Manufacturing System (FMS). An FMS is the system configuration characterized by the highest level of flexibility.

The testing activities have been carried out considering a machine database composed of general purpose, drilling and roughing machines. The latter two machine types are considered dedicated resources.

The analysis has been applied to a set of production problems characterized by a family of products, each of them with its specific set of operations to be machined. Moreover, a large set of different aggregate demand volumes has been considered keeping fixed the mix ratios. The analysis has ranged from low aggregate demand volumes requiring only one machine, to large size systems characterized by many machines. In this way it is possible to evaluate the range of production requirements where the selection of dedicated resources results more appropriate.

The evolutionary concept is not addressed in this section and a static analysis is considered. Therefore the production problems are characterized by a scenario tree consisting of only one node, i.e. the FFMS design model is simplified to a single-stage instance. The impact of dynamic and stochastic aspects of the production problem will be addressed in Chap. 10, where the system performance estimated by the FFMS design model will be compared to simulation results and the value of the stochastic programming approach will be calculated for planning horizons with more than one decision stage.

7.9.1 Test Case

The production problems defined to test the FFMS design approach have been built considering a product family consisting of ten mechanical components. Three of these product codes (i.e. codes 240, 280, 900) are described in Sect. 10.1, while the other ones are variants of the products presented in the same section, i.e. products obtained removing some machining features from the original versions. The number of workingsteps for every product ranges from 4 to 19.

Analyzing the process plan of the products it is possible to calculate the global cutting time required by the machining operations of every product. The part family can be characterized according to the cutting time that is spent to execute the different operation types. Considering the types of dedicated machines (i.e. drilling and roughing machines), two classification drivers have been defined:

- roughing or finishing operations;
- drilling or non-drilling operations.

A dedicated machine can perform only a subset of the operations and in particular a drilling machine can execute only drilling operations (both roughing and finishing), while a roughing machine can process only roughing operations (both drilling and non-drilling). A general purpose machine is a 4-axis machining center that can execute all the required operation.

Four test cases have been defined varying the set of products. In the first test case only real products have been considered, while in the other cases also product variants have been introduced. The part mix of the four cases has been defined to characterize the test cases with different percentages of the operation types. This means that the percentage of cutting time dedicated, for instance, to roughing operation is not constant over the test cases. Herein, the percentage of operation types has been changed to study how it can impact on the selection of the machine types. The operation percentages of the four test cases are reported in Table 7.17.

Table 7.17 Test cases and operation type percentages

Test case	Roughing operation time percentage	Finishing operation time percentage	Drilling operation time percentage	Non-drilling operation time percentage
1	60%	40%	50%	50%
2	60%	40%	30%	70%
3	40%	60%	50%	50%
4	40%	60%	30%	70%

The aggregate demand of the four basic test cases has been defined aiming at having an equal total cutting time for the different cases, thus allowing a better comparison of the test results. The aggregate demand has a deep impact on the optimal system solution and on the possibility of customizing the flexibility of the system. Therefore, starting from the initial aggregate demand that guarantees an equal total cutting time for the four test cases, 250 different levels of aggregate demand volume have been defined. The demand volume of each level is 10% greater than the demand of the previous level. This means that 1000 experimental conditions have been tested. The first level of aggregate demand has been set to a value so that the designed system requires only one machine.

In general process plans can be optimized according to the machine type where the machining operations are executed. However, the simplifying hypothesis is made that the cutting time of the operations does not depend on the machine type. Herein the machine architecture and performance have an impact only on the rapid time and on the pallet change time.

A general purpose is more expensive than a dedicated machine in term of investment cost because it is endowed with higher flexibility. For the sake of simplicity, all the dedicated resources (i.e. drilling and roughing machines) are assumed to have the same investment cost. Data related to resource investment costs are usually difficult to be collected and often cannot be compared. For this reason, the cost of dedicated machines has been set assuming a percentage reduction of the general purpose machine cost. Three levels of cost reduction have been considered: 10%, 30% and 50%. A reduction lower than 10% could hardly justify the investment to build a dedicated machine instead of a general purpose one, while a reduction greater than 50% can be reached only in particular situations. For each of the 1000 experimental conditions, the system design model has been launched four times: once to design an FMS (i.e. a system with only general purpose machines) and three times to design an FFMS characterized by the different cost reduction levels for the dedicated machines. The three FFMS configurations have been named FFMS-10, FFMS-30 and FFMS-50% when the cost reduction of dedicated machines is equal to 10, 30 and 50%, respectively.

7.9.2 Profitability of FFMS Solutions

The FFMS design model presented in Sect. 7.6 has been implemented in ILOG OPL language and ILOG CPLEX 10.1 in a C++ environment.

As anticipated in the previous sub-section, the experimentation has been carried out considering at first a machine database composed exclusively of general purpose machines and then including in the database also dedicated resources. The comparison of FMS and FFMS investment costs highlights that focusing system flexibility is profitable for all the considered test cases. This means that the introduction of dedicated resources within the machine database

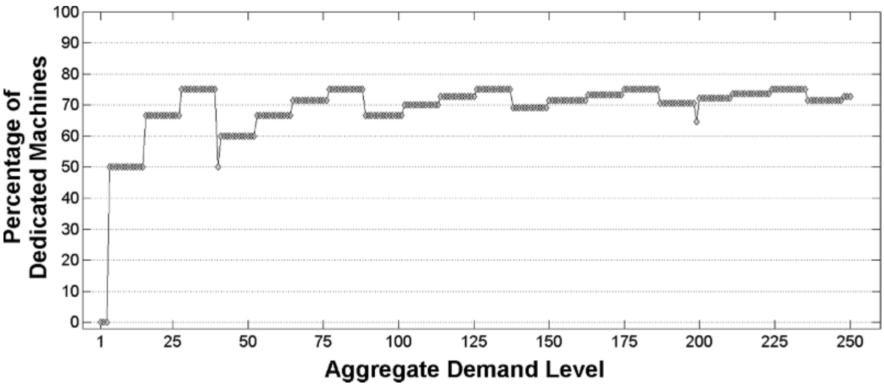


Fig. 7.10 Percentage of dedicated machines for the FFMS-50% solution in Test Case n.1

represents an option to provide a winning system solution. In particular, the option of focusing the flexibility can be better exploited when the aggregate demand increases. Indeed, mid-high levels of demand require to select more resources thus enabling the customization option. This phenomenon can be noticed in Fig. 7.10 where the percentage of dedicated machines is reported for the FFMS-50% solution of Test Case n.1. The graph clearly shows that for low demand levels it is more difficult to insert dedicated machines in the system. It is also clear from the graph that as soon as the demand increases dedicated machines become a profitable option.

The mean percentage of dedicated machines calculated over the 250 aggregate demand levels is reported in Table 7.18 for the three types of FFMS solutions. The results show that both the cost of the dedicated machines and the characteristics of the production problem have an impact on how the system flexibility can be focused. The test cases require different degree of flexibility and, in particular, Test Case n.1 allows to design the production systems characterized by the lowest level of flexibility.

After an analysis of the FFMS architecture solutions, also an economic analysis can be carried out considering the performance indicator $\Delta cost\%$ (7.50) that is defined as the percentage difference between the FMS cost and the FFMS cost.

$$\Delta cost\% = \frac{(FMScost) - (FFMScost)}{(FMScost)} \cdot 100 \tag{7.50}$$

Table 7.18 Mean percentage of dedicated machines in FFMS solutions

System configuration	Test Case n.1	Test Case n.2	Test Case n.3	Test Case n.4
FFMS-10%	64.76	55.29	49.83	39.83
FFMS-30%	68.80	62.34	55.28	51.10
FFMS-50%	69.14	63.48	55.51	52.96

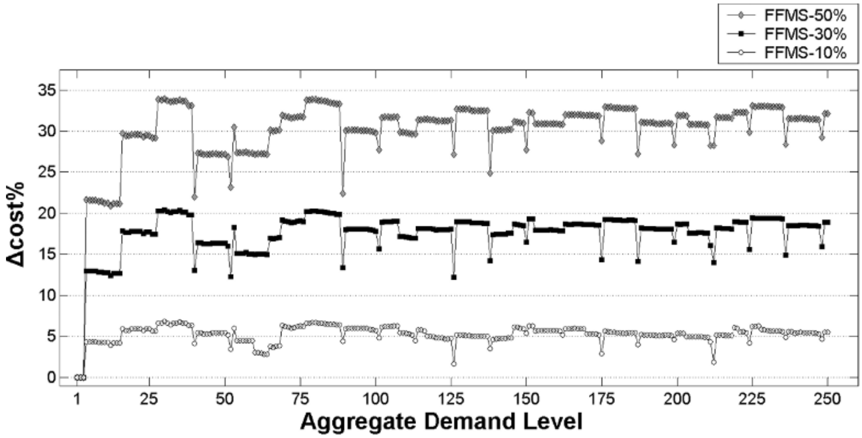


Fig. 7.11 Profitability of FFMS solutions in Test Case n.1 – Δ*cost%* indicator

Through this parameter it is possible to evaluate how the cost of dedicated machines and the ratio of operation types influence the FFMS profitability. Figures 7.11, 7.12, 7.13 and 7.14 show the profitability of the FFMS solutions as a function of the aggregate demand. Each figure refers to a different test case and in each figure the three FFMS solutions are reported.

Table 7.19 reports the mean values of Δ*cost%* for each test case and for each type of FFMS solution (i.e. FFMS-10, FFMS-30 and FFMS-50%) according to the cost reduction of the dedicated machine.

The results show that by introducing in the database of selectable machines some less expensive dedicated machines it is possible to significantly affect the

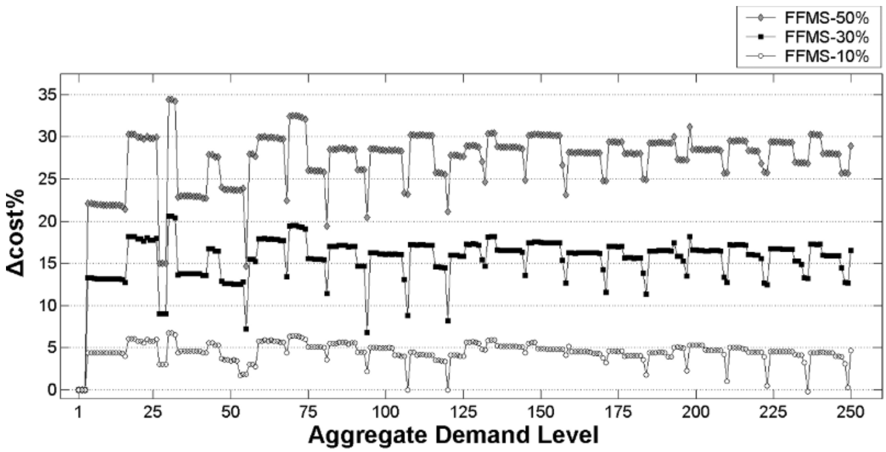


Fig. 7.12 Profitability of FFMS solutions in Test Case n.2 – Δ*cost%* indicator

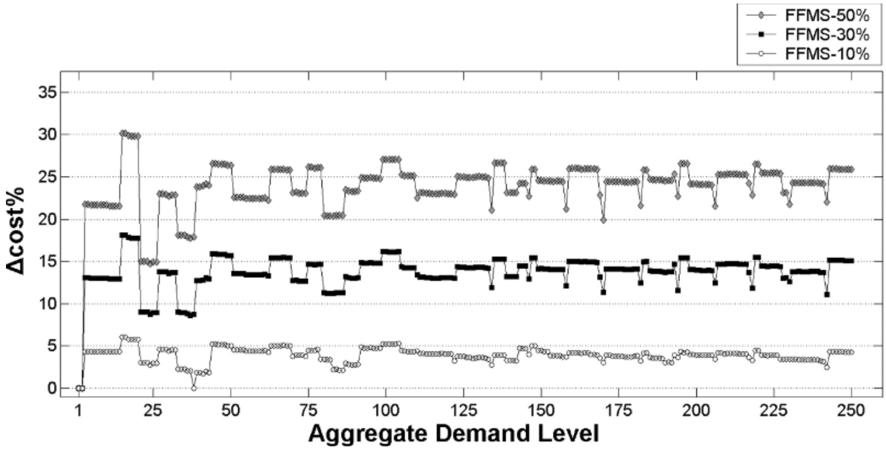


Fig. 7.13 Profitability of FFMS solutions in Test Case n.3 – Δ*cost%* indicator

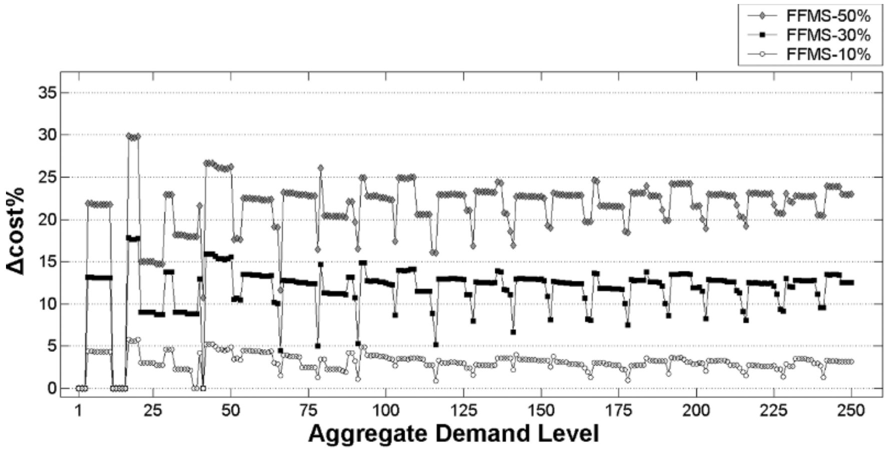


Fig. 7.14 Profitability of FFMS solutions in Test Case n.4 – Δ*cost%* indicator

cost of the whole system. For instance, considering Test Case n.1, if the machine database includes selectable resources whose cost is 30% less then the cost of general purpose machine, then the designed FFMS system allows to reduce the

Table 7.19 Mean profitability of FFMS solutions – mean Δcost%

System configuration	Test Case n.1	Test Case n.2	Test Case n.3	Test Case n.4
FFMS-10%	5.27	4.51	3.93	3.08
FFMS-30%	17.55	15.57	13.74	11.69
FFMS-50%	30.10	27.18	23.85	21.21

Table 7.20 System classes

System class	Number of machines in the FMS solution	Demand level range
Small size	From 2 to 3	4–27
Medium size	From 4 to 5	28–52
Large size	From 6 to 8	53–89

investment by 17.55% on average compared to a traditional parallel machine FMS. However, the aggregation of all the 250 demand levels belonging to a test case can be misleading, because small size systems would be considered together with large size systems. Therefore, the demand levels of each test case have been grouped according to the dimension of the FMS solution that is required to address the production problem. Three classes of manufacturing system have been defined as reported in Table 7.20.

Very small systems with just one machine have not been considered because they are not interesting for the application of the FFMS approach: indeed, no dedicated resource can be acquired. Also very large systems with more than 8 machines have been discarded because this kind of manufacturing systems is rather rare to be found in practice.

Table 7.21 enriches the results presented in Table 7.19 by reporting the mean FFMS profitability for each system class.

In general, both the system size and the cost of the dedicated machines have an impact on the profitability of the FFMS solutions: the larger is the system size and the cost reduction of dedicated machines, the higher is the profitability. However, even for small size systems the FFMS solutions have an interesting profitability; for instance, the FFMS-30% solution for small systems in the Test Case n.2 gives a mean profitability of 14.96%. This is relevant especially considering that system investment costs are typically in the order of millions of Euros. Moreover, Tolio and Valente (2006) have already shown that the cost-effectiveness of the FFMS solution improves if the machine database is composed of different machine types (in terms of operations that can be performed).

Table 7.21 Mean profitability of FFMS solutions for each system class – mean Δcost%

System configuration	System class	Test Case n.1	Test Case n.2	Test Case n.3	Test Case n.4
FFMS-10%	Small size	5.03	4.94	4.38	3.25
FFMS-10%	Medium size	5.83	4.57	3.53	3.41
FFMS-10%	Large size	5.27	5.05	3.99	3.30
FFMS-30%	Small size	15.22	14.96	13.24	9.92
FFMS-30%	Medium size	17.83	14.36	12.96	11.83
FFMS-30%	Large size	17.78	16.48	13.44	11.98
FFMS-50%	Small size	25.41	24.99	22.11	16.58
FFMS-50%	Medium size	29.91	24.63	22.92	21.30
FFMS-50%	Large size	30.57	27.98	23.38	21.47

In this sense, the development of a heterogeneous machine database underpins the profitability of the solution.

As previously stated, the test cases differ in the technological characteristics of the products composing the part family. The results show that also the type of operations to be machined in the system have an impact on the profitability of the FFMS solutions: the higher is the fraction of roughing and drilling operation, the higher is the profitability of FFMS solutions. Test Case n.1 has the largest amount of roughing and drilling operations and it is the test case where the mean FFMS profitability is the highest for all the three FFMS solutions and for all the system sizes (Table 7.21). Indeed, in this test case it is easier to focus the production flexibility by inserting dedicated machines in the system. The FFMS profitability is low in Test Case n.4 which is characterized by the lowest percentage of cutting time spent for drilling and roughing operations; Test Case n.4 represents a production problem requiring more flexibility than the other cases: therefore, focusing the flexibility becomes quite difficult.

Observing Figs. 7.11, 7.12, 7.13 and 7.14, it can be seen that the FFMS profitability grows when the aggregate demand increases, until it reaches an asymptotic value. This asymptotic value depends on the production problem characteristics (i.e. ratio of operation types) and on the cost of the dedicated resources, as it has already been shown for the mean profitability (Tables 7.19 and 7.21). However, the FFMS profitability does not monotonically increase and even with high demand levels there are fluctuations around the asymptotic value. This fluctuations are mainly caused by the discrete nature of the resources. High peaks represent situations where the difference between the FFMS and the FMS solutions is enhanced, while low peaks coincide with non favorable cases where the FFMS solution is closer to the FMS one. The frequency and the magnitude of the fluctuations are influenced by the type of production problem and also by the cost of the dedicated resources.

A low fraction of drilling and roughing operations (e.g. Test Case n.4) leads to more frequent fluctuations because the dedicated resources cannot be well saturated. Indeed, the amount of drilling and roughing cutting time depends on the aggregate demand and in some demand levels it is difficult to keep stable the proportion of dedicated resources because of scarce saturation.

The cost of the dedicated machines impacts on the magnitude of the fluctuations. A high cost difference between general purpose and dedicated machines leads to larger fluctuations because the reduction of the fraction of dedicated machines has a deep impact on the system cost.

The transient reduction of FFMS profitability when the aggregate demand grows can be explained by analyzing two main performance indicators:

1. Saturation of the machines (general purpose or dedicated) in the FFMS solution;
2. Saturation of the carrier in the FFMS solution.

When the capacity of the general purpose machines has been saturated, while the dedicated machines are still unsaturated, it is necessary to acquire a new general purpose machine as soon as the demand grows, because the number of general purpose machines is not enough to process all the finishing and/or non-drilling operations. This leads to acquire a new general purpose machine thus reducing the fraction of dedicated resources in the system and also the FFMS profitability.

The carrier gets saturated earlier in the FFMS solutions than in FMS solutions. Indeed, some pallets have to visit both general purpose and dedicated machines in an FFMS. As a consequence, the number of carrier missions increases. When the carrier is saturated there are two viable reactions:

- Acquisition of an additional carrier;
- Reduction of the number of operations assigned to the dedicated machines in order to decrease the number of carrier missions. This action could require to acquire more general purpose machines.

The choice of the best reaction depends on the cost of the carrier and on the economic difference between a general purpose and a dedicated machine. In both cases the FFMS investment cost gets closer to the FMS investment cost.

The evolution of FFMS profitability can be better understood paying attention to the example represented by Test Case n.1. The analysis of the most significant phenomena taking place within the initial 80 demand levels is reported in Table 7.22. These phenomena explain the fluctuations of the FFMS profitability.

The number of general purpose and dedicated machines in the FFMS solutions of Test Case n.1 can be further analyzed looking at Figs. 7.15 and 7.16.

Table 7.22 Phenomena influencing the FFMS profitability in Test Case n.1

Demand Level	Explanation of significant phenomena
1	The FMS and the FFMS solutions consist only of one general purpose machine and one carrier.
4	One general purpose machine is not sufficient. The first dedicated machine is added to the FFMS solutions and the FFMS profitability grows.
16	The second dedicated machine is added to the FFMS solutions. The FFMS profitability grows.
28	The third dedicated machine is added to the FFMS solutions. The FFMS profitability grows.
40	The unique general purpose machine is saturated in the FFMS solutions. One dedicated machine is substituted by a general purpose one, thus reducing the cost difference between the FFMS and FMS solutions.
41	Also the dedicated resources are saturated in the FFMS solutions. The third dedicated machine is added again to the FFMS solutions and the FFMS profitability grows.
52	The carrier is saturated in the FFMS solutions. In the FFMS-50% and FFMS-30% solutions this problem is faced by acquiring a second carrier, while in the FFMS-10% by substituting a dedicated machine with a general purpose one in order to reduce the number of carrier missions. The FFMS profitability decreases.

Table 7.22 (continued)

Demand Level	Explanation of significant phenomena
53	Machines are saturated in the FMS and the FFMS solutions and it is necessary to acquire an additional machine. In FFMS-50% and FFMS-30% solutions a dedicated machine is acquired, while in FFMS-10% two dedicated machines are purchased and a general purpose is dismissed. In these new configurations the machines are less saturated and it is possible to better manage the assignment of the operations to the different machine types in order to reduce the number of pallets that need to visit more than one machine. In this way the number of carrier missions is reduced and it results that one carrier is sufficient in all the FFMS solutions. Compared to the previous case (demand level 52), the higher fraction of dedicated machines and the dismission of a carrier lead to increase the FFMS profitability.
54	Again the carrier is saturated in the FFMS solutions. In the FFMS-50% and FFMS-30% solutions this problem is faced by acquiring a second carrier, while in the FFMS-10% by substituting a dedicated machine with a general purpose one in order to reduce the number of carrier missions. The FFMS profitability decreases.
63	The carrier is saturated in the FFMS-10% and the second carrier is acquired. In this way the number of dedicated and general purpose machines becomes equal in all the FFMS solutions, since the effect of the carrier saturation is removed.
65	The fifth dedicated machine is added to the FFMS solutions. The FFMS profitability grows.
77	The sixth dedicated machine is added to the FFMS solutions. The FFMS profitability grows.

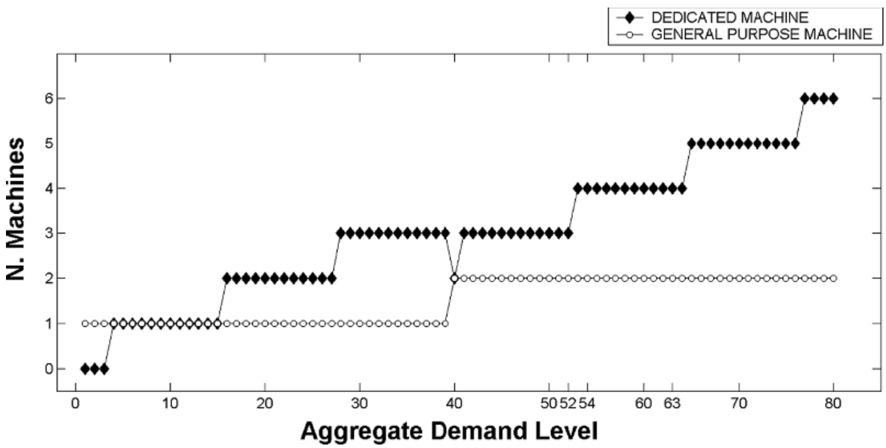


Fig. 7.15 Machine types in Test Case n.1 for FFMS-30% solution

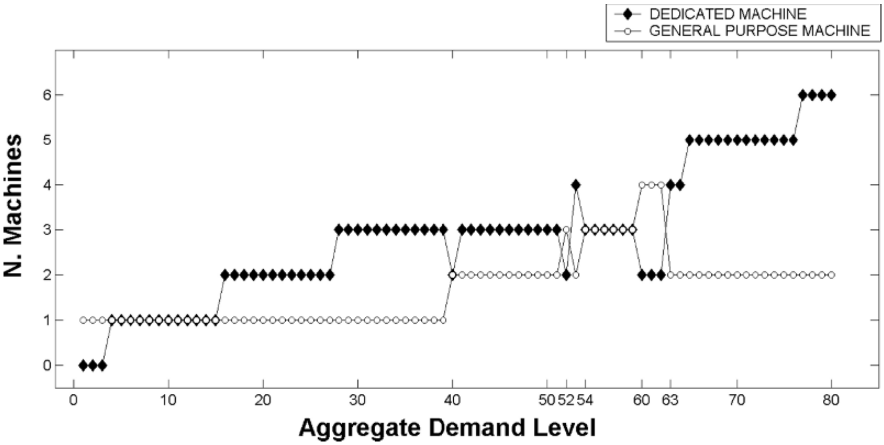


Fig. 7.16 Machine types in Test Case n.1 for FFMS-10% solution

The number of machines in the FFMS-30% solution for Test Case n.1 corresponds exactly to the number of machines in the FFMS-50%. Figure 7.15 reports the solution in the case of FFMS-30%. At low demand volumes there is only one machine in the system; this machine must be a general purpose because it is necessary to process all the operation types. At demand level n.80 there are 6 dedicated machines and 2 general purpose: the high number of dedicated machines is related to the low level of flexibility required by Test Case n.1.

By comparing Figs. 7.15 and 7.16, it can be seen that until demand level n.51, the system solutions in the FFMS-10% and FFMS-30% for Test Case n.1 are identical. In the range between demand levels n.52 and n.62 there is a significant difference. This difference is due to the carrier effect on the system. In the FFMS-30% case the cost difference between a general purpose and a dedicated machine is greater than the cost of a carrier; on the other hand, in the FFMS-10% case the cost difference between a general purpose and a dedicated machine is lower than the cost of a carrier. Therefore, in the FFMS-30% solutions it is effective to acquire many dedicated machines even if it is necessary to buy an additional carrier to cope with the increased number of carrier missions; the acquisition of the second carrier is made at demand level n.52 (see Table 7.20). Instead, in the FFMS-10% case the acquisition of the second carrier is postponed as much as possible; in order to reduce the number of carrier missions, after demand level n.52 the flexibility of the system is less focused because general purpose machines are acquired instead of dedicated ones. Anyway, after demand level n.63 it is strictly necessary to buy the second carrier also for the FFMS-10% solution and it is possible to focus again the system flexibility.

The carrier saturations for FMS, FFMS-10% and FFMS-30% solutions in Test Case n.1 are reported in Fig. 7.17. When the number of carriers in the

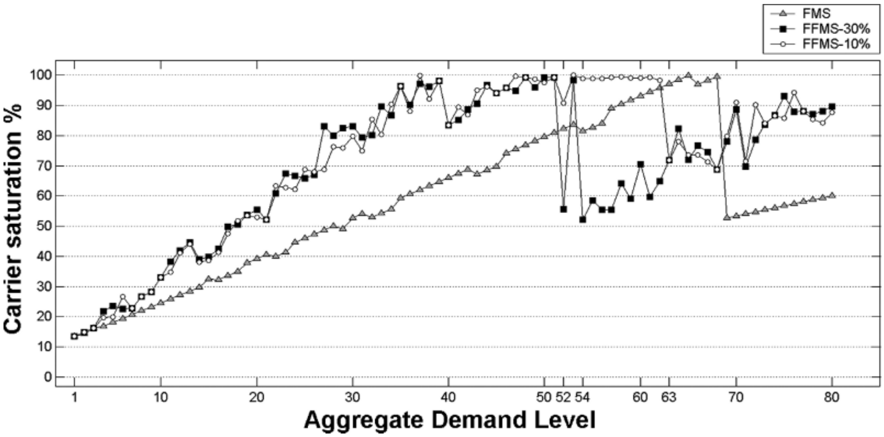


Fig. 7.17 Carrier saturation in Test Case n.1

system solutions is equal (i.e. until demand level n. 51), then carrier saturation in the FFMS is higher than in the FMS because some pallets need to visit more than one machining center, thus leading to a larger number of carrier missions and a higher saturation. The FFMS-10% solution avoids to acquire the second carrier until demand level n.63; therefore the carrier saturation remains close to 100% between demand levels n.52 and n.62.

Finally, it can be noted that in the FMS solution the second carrier is purchased at the demand level n.69.

The analysis carried out for the initial demand levels of Test Case n.1 can be extended also to higher demand levels. Moreover, in the other three test cases the phenomena taking place are similar to those described in Table 7.22.

7.10 Conclusions

This chapter has presented an FFMS design approach which can be fully integrated in the FFMS design architecture presented in Chap. 1. The key points of the approach consist of the adopted technique (i.e. stochastic programming) and in the structured approach to the problem that requires a detailed formalization of the production problem (i.e. demand and technological information).

The testing results show that an FFMS solution can yield a relevant economic advantage at a system level if a machine tool builder succeeds in developing dedicated machines requiring a lower investment cost. Dedicated resources with a much lower investment cost have a two-fold impact:

- A greater amount of cost reduction can be transferred at a system level;
- FFMS solutions are more robust than FMS solutions towards changes in the aggregate demand.

Indeed, focusing the system flexibility allows the machine tool builders to provide solutions which are cost-effective and sufficiently robust if compared to traditional FMSs. In this sense, even if the industrial impact of FFMS is still weak, the obtained results suggest the opportunity to investigate new technological solutions and new system architectures that can lead to competitive advantages, thus increasing the chance to win the orders.

7.11 Open Research Issues

The research about Focused Flexibility Manufacturing Systems has still to address some important topics:

- modeling of short- and mid-term variability of the production problems during the system design process;
- the variability related to the manufacturing system (i.e. resource availability) should be further investigated by the future manufacturing system design models;
- the problem of manufacturing system design is characterized by important intangible criteria that should be considered together with quantitative aspects in a multi-criteria decision approach;
- the modeling of the ramp-up phenomenon can be further enhanced including, for instance, the learning process which influences the resource efficiency and availability as well as the impact of the ramp-up of each resource on the whole system efficiency;
- the development of a support tool for machine tool builders requires to model also the capacity of the plant of the machine tool builder system (i.e. the plant where manufacturing systems are produced), that consists of different divisions (e.g. assembling, wiring, testing, etc.). The resources composing the designed manufacturing system can be built using internal capacity or more expensive extra capacity (e.g. outsourcing, overtime work). This analysis could influence the type of machines that the machine tool builder sells: for instance, it could be more profitable to sell the machine types whose requirements best fit the available capacity of the plant of the machine tool builder;
- the machine tool builder should also have the possibility to operate on some control parameters such as the due date of the designed system and the preferences for the type of resources to be installed in the system configuration;
- finally, the opportunity to extend the Focused Flexibility approach to different production processes (e.g. assembly) and production contexts (e.g. aeronautic field) should be evaluated.

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Chapter 8
System Life-Cycle Planning

Marco Cantamessa, Carlo Capello and Giuseppe Cordella

Abstract This chapter introduces a computational model to support the system user along the decision making process regarding the type and timing of system configurations to be acquired and the appropriate flexibility degree. Based on the empirical evidence described in Chap. 2, Focused Flexibility Manufacturing Systems (FFMS) seem to be a viable alternative to solve the classical dichotomy between rigid and fully flexible systems. This focused flexibility concept, as introduced in Chap. 3, can be a valuable solution for manufacturing firms to satisfy the market needs. Previous chapters tackled the system flexibility design process from the machine tool builder standpoint. Once the potential system configurations have been defined and the capital outlays required for acquiring and/or transitioning among them have been quantified, the machine tool builder makes an offer to the system user. The latter needs to select the most profitable solution by evaluating the performance generated by each configuration under different demand profiles from a financial point of view. This decision is supported by two optimization models, one static – i.e. not affected by the time dimension – and one dynamic, wrapped up in a valuation model which simulates a profit function on different variable values over a multi-period time horizon, matching the user's expected demand levels with his manufacturing strategies.

Keywords System life-cycle planning · Mixed-integer linear programming · Focused flexibility · Real options

8.1 Introduction

Manufacturing small and medium-sized enterprises (SMEs) are to maintain and upgrade their manufacturing plants in order to constantly align their offer to market requests and improve production performance. This is a

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tough problem, as they have to find and implement the optimal mix between manufacturing flexibility and capacity and adjust it over a long-term horizon (Tolio and Valente 2006). If they do not do so, they risk not being able to satisfy their customers and reach the internal performance goals.

An investment decision in a manufacturing system, rather than in a single machining center or cell, usually derives from a negotiation between the manufacturing company (i.e. the system user) and one or more suppliers (i.e. machine tool builders). The process is complex as it involves different objectives, boundaries and perspectives (Tolio et al. 2007). The system user usually looks for something that enables it to face the current and expected uncertainty on the market and limit the investment as much as possible. The machine tool builder aims to satisfy the user requests and, on the other hand, maximize its profit by keeping costs down and revenues up, consistently with its capacity constraints. Due to these asymmetries, the result of the negotiation can easily be a sub-optimal solution.

The negotiation process includes some basic steps that can be repeated a number of times. These steps are sequential and iterative, that is they can be looped several times before converging to a final result. The system user at first develops a business strategy and structures the manufacturing plant so as to align the composition and timing of part mix with market demand. The user generally works with demand projections and searches the manufacturing configuration that matches these expectations within a given budget. The machine tool builder works on this information, and adds some of its own internal constraints such as capacity and time availability. It designs some manufacturing alternatives characterized by different flexibility degrees that can be used and adapted to the expected production paths laid out from the client over a multi-year horizon. The spectrum of manufacturing solutions can be rather broad: the machine tool builder may propose highly flexible machining solutions, close to the FMS concept, that allow the client to process a wide variety of components and materials, albeit with a high initial investment and a complex execution. On the other hand, it can design a system with rigid machines, which are generally less costly and complex to handle than an FMS – assuming production capacity as constant – but limited to a narrower range of part types. In addition, according to the trends highlighted by empirical evidence (see Chap. 3), the system designer can propose something closer to the FFMS concept, i.e. a solution whose flexibility is specifically tailored to the client's needs, and that gives the opportunity for further upgrades and reconfigurations. In the end, the designer wraps all the designed solutions up in a commercial bid, reporting investment and switching costs for all potential solutions and related reconfigurations, plus additional boundaries and performance specifications.

Once the system user receives the bid, it faces the problem of assessing all possible configurations and reconfigurations. The two "extreme" choices of the FMS and the rigid manufacturing system entail the risks of respectively not being able to pay the investment back in an acceptable time span, or not being able to follow shifts in demand. Of course, other possibilities are available, such as planning to follow changes in demand with either outsourcing or reconfiguration of manufacturing resources.

The following section reviews some literature about the system life-cycle planning problem and describes inputs and outputs for the valuation model. Section 8.3 introduces in-depth the valuation model structure and Sect. 8.4 describes the set of indexes that will be used in the model. Sections 8.5 and 8.6 analyze the two components of the model, namely the static and the sequential models. In the end, Sect. 8.7 shows an application model example and Sect. 8.8 concludes the chapter.

8.2 Introduction to Life-Cycle Planning

Empirical evidence discussed in Chap. 2 shows that system users usually have a hard time in assessing the proposed manufacturing solutions and selecting the one that matches current and expected market needs. Planning and evaluating flexible capacity is hard, as many conflicting objectives and constraints are to be considered: maximizing profit; minimizing risk; lowering initial investments; increasing capacity and flexibility according to the market needs; reducing upstream dependency on outsourcers and sub-contractors; decreasing production penalties; maximizing the recovery value for each legacy resource. In addition, the interaction between system user and system designer makes the problem more complex given that new objectives and constraints are to be integrated with the counterpart's ones. Sometimes manufacturing SMEs do not even realize such complexities and tend to make very rough assessments and use their experience to plan and decide on their manufacturing capacity. They do not make a thorough validation for consistency with their business strategy, company skills, competencies, and market evolutions. They do perceive the problem though, which leads to the need for methods and tools which may help in rationalizing the relevant information and plan the investment for a new manufacturing system over its life-cycle.

As a large body of literature proves, the problems of planning and evaluating investments in manufacturing flexibility over the long-term period have been deeply investigated. This is a tough as well as necessary activity to profitably operate in rapidly changing and risking environments. Firms must design their manufacturing plant flexibility and then make operating decisions to satisfy their profit objective, subject to multiple boundaries. Cheng et al. (2003) interpreted this problem in a chemical company as "design/investment planning under uncertainty" and investigated it from the whole company perspective in order to consider all the potential complexities. They tried to capture and solve the difficulty for the executive management in satisfying conflicting goals as maximizing expected profit, minimizing risk, sustaining long-term viability and competitiveness. They considered different kinds of uncertainties including market conditions (part type, demand, price, etc.) and technology improvements (timing and magnitude of future technology breakthroughs such as improved flexibility degrees) and incorporated upper-level design and lower level production decisions at each period of the decision process. Technically, they modeled this problem as a Markov decision process with recourse that considers decision making throughout the process life-cycle. This leads to a multi-objective Markov decision problem, searching for Pareto optimal design strategies that prescribe design decisions for each state the environment and process could occupy. The final outcome is an intensive computational algorithm that is hard to be applied to a realistic problem due to a matter of dimensionality and the need of approximations that may heavily distort the results. Perrone et al. (2002) studied this problem from the manufacturing company perspective, and developed a decision support model for investment decisions in flexible systems. They identified three sequential decision phases: strategic design, production system configuration and detailed design. They then developed a theoretical framework in order to assess different system configurations on the benefits due to economies of scope associated with flexible manufacturing systems versus dedicated systems, and support long-term capacity decisions. Matta et al. (2001) proposed an integrated approach for supporting firms in their decisions in configuring and dimensioning automated production systems. The objective of the method is to identify a set of alternative production systems among which the manager of the firm can select the one he considers the best. For this purpose, the method works with a set of performance indicators to enable the decision-maker to calculate the expected net present value of the investment in several alternative configurations. This method would therefore be useful to choose the flexible system even though it would need further modifications to include the reconfiguration concept proper for the FFMS case. Choi and Kim (1998) developed a comprehensive approach for measuring flexibility in manufacturing systems in terms of total processing time. It is useful to have a major insight into how to appreciate manufacturing flexibility and which the related lower inefficient time benefits are, however this approach does not include any decision variables, and therefore does not support capacity planning decisions. Elkins et al. (2004) developed two simple decision models with the purpose of providing insight in analyzing business case for investment in agile manufacturing systems (AMSs), compared to FMSs and rigid systems. The outcome is a couple of models that can support the decision-making process and are simpler than the ones developed by the above contributions. However, one of them is based on a set of qualitative comparison factors that are useful to develop a profile for each system solutions but does include neither decision variables nor time axis. The other one formalizes the problem of modeling varying demand and part mix by using decision trees: however event probabilities are subjectively set and branches are too much simplistic to be used for modeling complex problem such as system life-cycle planning over time.

Some of these authors deal with the problem of choosing among rigid and flexible systems, but either do not take the possible evolution of the system into account, or do so with models that are highly complex from the computational point of view and as far as practical usability is concerned. When dealing with the evolution of the manufacturing system and its potential reconfigurations[1] some authors tried to use the concept of "real option" in order to represent the potential for a production resource to be reconfigured sometime in the future. Bengtsson and Olhager (2001) used the concept of Real Option to represent the capability of a flexible system to be easily and cost-effectively adapted to different and new part mix compositions. Kulatilaka (1988) tried to capture the value of flexibility by valuing the opportunity for a flexible system to be reconfigured so as to easily switch to a new operating mode. He developed a model by using the Bellman equation of dynamic programming to establish which the optimal mode to operate at each time step was, given a system configuration and its potential operating modes with related switching costs. However, this model assumed that all the sources of uncertainty – as type of product, material, product geometry, etc. – were integrated within one source affecting the underlying asset. Then, the paper tackled the production problem by considering a simplified part mix as composed of two part types. However, when moving to a practical context, this approach becomes complex to be used and, most of all, understood. The many sources of uncertainty that affect a manufacturing system and the increasing computational complexity of the model when the number of variables increases (i.e. the part mix wideness) are the main elements that hinder the applicability of the "real option" approach to this problem, an approach which on paper would seem the most appropriate one to be used. Apart from this aspect, the use of this model applied to a complex real case generates as much complex results that are difficult to be understood and therefore hard to be proposed to a manufacturing company.

This chapter tries to bridge the gap present in literature and proposes an approach for supporting life-cycle decisions, which may at the same time capture the complexity of the manufacturing environment and still be simple enough to be applied by practitioners. To this purpose, it introduces mathematical programming models which can lead to an evolutionary manufacturing system solution that optimizes expected profit over a multi-period time horizon. This work is addressed to the system user in supporting his interaction with the machine tool builder, and the decisions he must take among the set of possible choices laid out by the latter. Therefore, the valuation model supports the decision making process that the system user has to accomplish in order to choose the kind of system configuration to acquire and to plan for its future potential upgrades. In the context of a small-medium enterprise (SME), the

[1] In order to have a major insight into the reconfiguration concept, please refer to Matta et al. (2008).

typical user of this model would be the upper management of the company, eventually supported by a consultant. In the case of larger firms, it could be a working group with representatives from production and finance. In this latter case, the model described in Chap. 5 would be targeted to top management, while the model discussed in this chapter would have production managers as main users.

The information required by this model derives from results emerging from the previous chapters of this book. Chapter 5 introduces the model that the system user utilizes to define the expected scenarios for its relevant production variables and represent them through a scenario tree (Tolio and Valente 2007; Cantamessa et al. 2007). Chapter 6 describes the manufacturing technology while Chap. 7 provides alternative solutions offering different degrees of flexibility.

The chapter follows the usual "system user vs. machine tool builder" framework according to the interaction setting described in Chap. 1. It formalizes the user's objectives and constraints and supports it throughout the system acquisition process, while taking for granted all the inputs deriving from the previous models.

In order to capture the real-world context of a manufacturing company, the model assumes that the client is already producing and selling goods on the market and has a manufacturing system that in a sense competes with the new proposed solutions. This means that – at the limit – the optimal solution suggested by the model could be not to invest at all and keep on producing with the legacy system. The model includes some budget constraints and a risk aversion parameter (i.e. the profit discount rate) that can affect purchasing decisions. Moreover, the model also allows to consider a technological path-dependency, which is important since this element arose quite clearly from the empirical evidence in Chap. 2. Switching from one solution to another one does not come for free, or with a cost which is simply equal to the additional investment in machinery. To this purpose, the model considers both generic switching costs (which can include factors such as training, decommissioning, etc.) and an initial inefficiency due to learning curve associated with operating new machinery.

Other elements affect both positively and negatively the final outlay as the variable costs and the recovery value of the current system. In fact, and as shown in Chap. 2, many firms prefer to maintain the current manufacturing system and handle uncertainty or changes in part mix or demand with different ways, such as outsourcing.

Figure 8.1 shows input and output for the valuation model.

The model processes all these inputs and generates a multi-period solution. It indicates the system solution to be acquired at the first time stage, the system reconfigurations to be operated the future time stages, and the related economic performance. These results are useful to support the system user in planning the system life-cycle and avoiding misalignments and problems that have been discussed in Chap. 2.

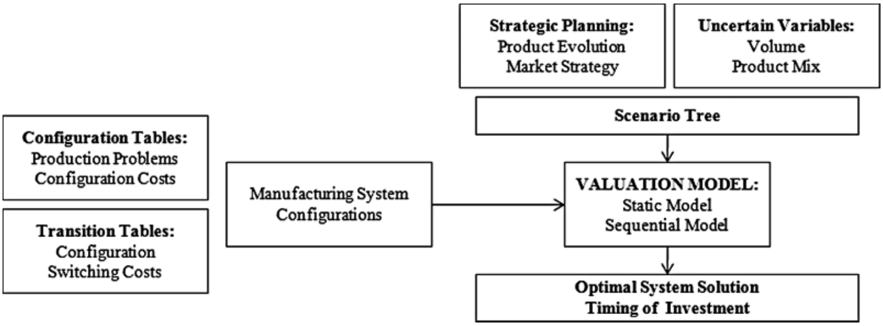

Fig. 8.1 Valuation model structure

8.3 The Valuation Model Structure

The valuation model is structured in two basic models: a Static Model and a Sequential Model. The first one considers the system performance as the manufacturing costs associated with a specific instance of the [scenario node – system configuration] set: it minimizes such costs while does not consider the time variable. Given a scenario node, s_1, and given a configuration, c_1, the Static Model returns the expected optimal manufacturing costs of c_1 under the scenario node s_1. It is important to notice that s_j represents the *j*th element of the scenario tree and is not time-dependent.

The second model (i.e. the Sequential Model) includes the time axis and divides it in discrete buckets. The model aims to identify the investment path that optimizes the trade-off between the expected investment and the operational costs along the time horizon. It guides the purchaser through the available configurations and points out those ones that come with the least overall expected costs under the expected demand scenarios. Therefore, the output is a set of solutions that is optimal from the aggregate standpoint instead of a set of locally optimal solutions. Both the time and the influence of previous choices lead to include the path-dependency phenomenon in the model so as to be more consistent with real manufacturing system configuring problems. In order to better clarify this concept, two cases are considered as extreme scenario: in the first case, it is assumed to have negligible switching costs while, in the second case, it is assumed to have very high switching costs. In the first case the Sequential Model will suggest selecting, at any time stage, the manufacturing system configuration that optimizes operational performance at each time stage, as if there was no dependence among time stages. In the second case the Sequential Model would suggest selecting the system configuration that makes the averaged best performance over all potential scenarios, and keeping on with that over the all planning horizon. In this latter case, it is likely that the configuration selected would not maximize the performance at any time stage (as it was with no switching costs), but it would maximize the performance over the multi-period horizon as it takes into account the switching costs as well.

The two problems have been developed as Mixed-Integer Linear Programming models to plan the basic machine to be selected on multi-period time by a deterministic setting.

Figure 8.2 shows the process layout to define a valid planning and valuation model, moving from the static to the dynamic one.

The Static Model receives two inputs: the sets of scenario nodes and the sets of alternative configurations. The first input is elaborated internally by the system user that is the addressee of this chapter. Chapter 5 describes how the system user should generate a set of scenarios based on some uncertainty variables (part mix and volumes) and company manufacturing strategies (i.e. focalization, differentiation and diversification). Each scenario is characterized by a production problem in terms of part mix composition and volumes to be produced, plus some geometrical and technological peculiarities. The second input derives from the interaction between the system user and machine tool builder. Once the system user has a projection of the expected demand scenarios, it submits this information to the machine tool builder, who develops a set of manufacturing system configurations. Each configuration is able to process a portion of a demand scenario according to the boundaries and the optimizing criteria set by the machine tool builder. This admissible production domain is expressed in terms of linear constraints and can be represented as a polyhedron region of part mix quantities that can be produced (see Sects. 4.5 and 7.4.4; Tolio and Valente 2007, 2008; Fig. 8.3 for a graphical representation). Chapter 4 has described how problem information has been formalized and Chap. 7 has introduced the system design process from the machine tool builder side. It is worth highlighting that each configuration can be a suboptimal solution for the client because it has been formulated and planned according to the machine tool builder's optimizing criteria as well. The Static Model processes these inputs and individually considers each [scenario node – configuration alternative] instance, and generates two outputs. The first one is composed of the costs sustained by the system configuration to process the production problem paired off with each scenario node. Performance are then stored in the Performance Matrix. The second output is the set of costs to switch from a configuration to another one. These costs are stored in a Switching Costs Matrix.

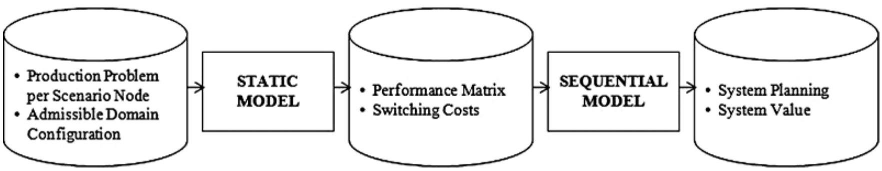

Fig. 8.2 Valuation model process

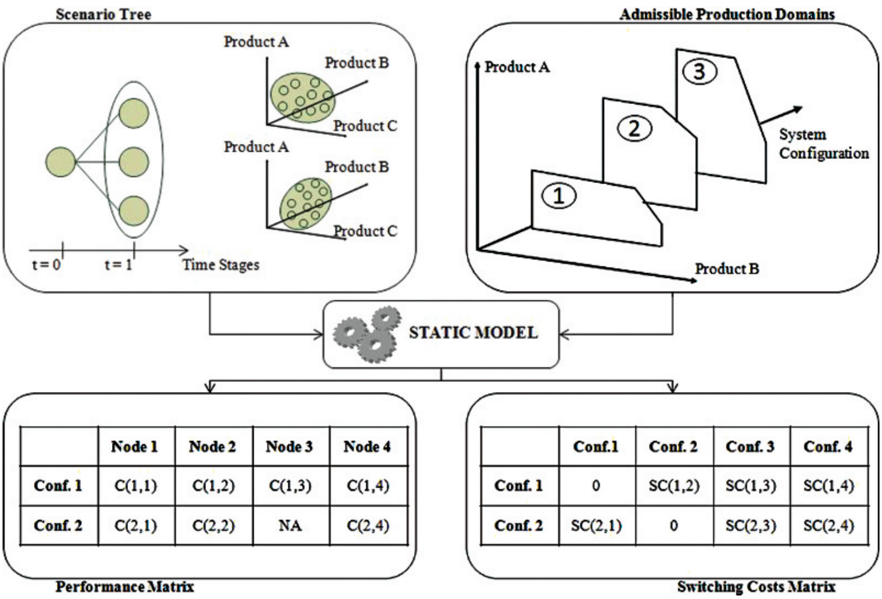

Fig. 8.3 Inputs and outputs from the static model

The Static Model outputs are then loaded into the "Performance Matrix" (PM) and the "Switching Costs Matrix" (SM) of the Sequential Model. In addition, the "Sequential Model" receives the information about the scenario tree in terms of occurrence probability for each scenario node as input (see Chap. 5 for an insight into the generating scenario node process).

The outcome leads to determine the optimal evolution of the system over the planning horizon (see Fig. 8.4 for the Sequential Model process).

8.4 Sets of the Valuation Model

The following sections will show how the static and sequential models have been formulated in terms of data, objective functions and constraints. Table 8.1 describes the indexes that will be used from now on.

8.5 Static Model

The aim of the Static Model is to calculate the parameter $b_{i,j}$ that is the system performance as manufacturing cost sustained by configuration i to face the production problem related to the scenario node j. Then, the model calculates the parameter $c_{w,i}$, that is the cost to switch from a configuration w to another

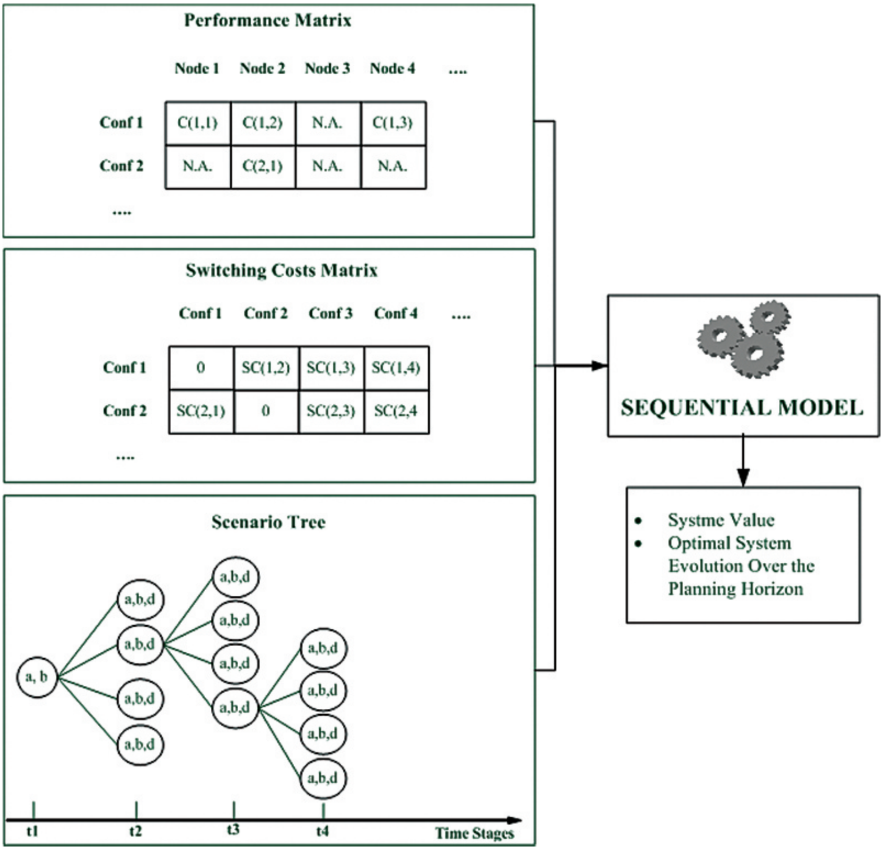

Fig. 8.4 Inputs and outputs from the sequential model

i in two subsequent time stages. The performance value comes from solving a minimum cost optimization problem including part mix demanded by the market, manufacturing capacity, production costs, and outsourcing and lost-sales penalty costs. Switching costs are calculated by solving a simple expression comparing two configurations in terms of number of available resources by alternative.

Table 8.1 Sets for the valuation model

Index	Definition
t	Time stages {1,...,T}
i, w	System configurations {1,...,M}
p	Part types of the mix {1,...,Q}
s	Type of resources per configuration *i* {1,...,R}
j	Scenario nodes {1,...,N}
k	Sub-scenarios for each performance value {1,...,K}

8.5.1 Performance Matrix

This section shows how the performance matrix is developed in terms of initial assumptions, data, decision variables and final formulation.

The assumptions are as follows:

- The system can produce internally a quantity $z_{i,s,p}$ of part type p using manufacturing machine s of configuration i as well as outsource production or undertake a penalty cost due to lost demand;
- Each configuration i is formalized as a linear constraint: given a part mix, a volume per part type p of the mix, and a configuration i including s manufacturing resources, the quantity that can be processed by a configuration depends on the hyperplane coefficient[2] of each resource.

Parameters are defined in Table 8.2.

The decision variable is reported in Table 8.3.

The problem objective function is then formulated as follows:

$$BBase_{j,i} = MIN\left\{\sum\nolimits_p \left[z_{j,i,p} \cdot CPI_{i,p} + \left(D_{j,t,p} - z_{j,i,p}\right) \cdot PCS_p\right]\right\}, \quad \forall i,j \quad (8.1)$$

Where $BBase_{j,i}$ is the performance of configuration i in facing the production problem associated with scenario node j. This value will be integrated with the "Sequential Model" in order to load the "Performance Matrix" as follows:

$$B_{j,k,i} = BBase_{j,i} \cdot \vartheta_k \quad (8.2)$$

Where the parameter θ_k is a multiplicative coefficient that indicates the up-down movements for each performance value and is used to set different cases, ranging from pessimistic to optimistic ($BBase_{i,j,t}$ is the most likely case). When θ_k is equal to 1, the problem is set on the base case. The optimistic case is given by the opportunity to improve the performance value (considering θ_k <1). On the other hand, the pessimistic case is given by the opportunity to worsen the performance value (considering θ_k >1).

The objective function is subject to the following boundaries:

$$\sum_p \alpha_{i,s,p} \cdot \left(1 + ru\_coeff_{i,s,p} \cdot NEW_{p,j,t}\right) \cdot z_{p,j,i} \leq \beta_{i,s} \cdot AVAIL_{i,s}, \quad \forall s,i,j,t \quad (8.3)$$

This constraint refers to the capacity boundaries for each resource s to produce part type p, for each configuration i at any scenario node j. The capacity constraint defines the admissible area for the configuration: constraints are supposed not to refer to each physical resource s, but to each type

[2] The hyper-plane coefficient is the operational time the resource s needs to complete a unit of product p of the mix.

Table 8.2 Model parameters

Parameter	Definition
$D_{p,j}$	Demand of part type p at scenario node j
$CPI_{p,i}$	Internal production costs associated with the production of part type p using the configuration i
$MMC_{p,s,i}$	Cost sustained by resource s of configuration alternative i to work part type p of the mix
PCS_p	Costs associated with the part of demand unsatisfied by internal production for part type p
$\alpha_{i,s,p}$	Hyperplane coefficient of resource s of configuration alternative i to produce part type p of the mix
$\beta_{i,s}$	Capacity boundary (right-hand side) of resource s of configuration i, in terms of total working time supported by each resource
PEN_p	Penalty costs whether it is produced less than demand for part type p
$COUT_p$	Outsourcing costs associated with producing (a part) of part type p externally
$AVAIL_{i,s}$	Availability as number of available resources s in the configuration i
$Ru\_coeff_{i,s,p}$	Additional time (expressed as a portion of normal hyperplane coefficient $\alpha_{i,s,p}$) required by resource s of configuration alternative i to ramp up each part type p when it is introduced for the first time. The chapter assumes that this additional time is sustained only for one time bucket (i.e. the first period in which a new part type p is introduced in the mix)
$NEW_{p,j,t}$	Is a Boolean variable and is equal to 1 if part type p is newly introduced under scenario j at time stage t, otherwise it is equal to 0
$CU_{s,i}$	Cost units sustained by resource s to work any part type p for a time unit by using the configuration i
θ_k	Multiplicative coefficient that indicates the k-th up-down movements for each performance value
$BBase_{j,i}$	Base performance of configuration i in facing the production problem associated with scenario node j
$B_{j,k,i}$	kth occurrence of performance of configuration i in facing production problem associated with scenario node j

of resource (i.e. if two physical manufacturing machines are equal, the right-hand of the constraint expression is twice as large).

PCS_p is the cost associated with the demand part for part type p that has not been satisfied by internal production. Its value is given by the following expression:

$$PCS_p = MIN\left[COUT_p, PEN_p\right], \quad \forall p \tag{8.4}$$

It is the minimum between producing externally costs (outsourcing solution) or undertaking penalty costs (unsatisfying demand solution).

Table 8.3 Decision variable

Variable	Definition
$z_{p,j,i}$	Quantity that can be internally produced for each part type p of the mix given the scenario node j and using configuration i

$CPI_{p,i}$ is the total working cost to produce internally a single unit of part type p of the mix. The value is given by expression 8.5:

$$CPI_{p,i} = \sum_{s} MMC_{s,i,p}, \quad \forall p, \forall i \tag{8.5}$$

It is the sum of costs sustained by all the s resources of each configuration i to produce a single unit of part type p. Therefore:

$$MMC_{s,i,p} = \alpha_{s,i,p} \cdot CU_{s,i}, \quad \forall s, \forall i, \forall p \tag{8.6}$$

8.5.2 Switching Costs Matrix

In addition to the "Performance Matrix", the Sequential Model receives the "Switching Costs Matrix" from the Static Model as input. Each cell of the Switching Costs Matrix is the cost to be sustained if the system user switches from a configuration to another one when moving to the next time stage. As obvious, there are zero values on the main diagonal of the matrix. The matrix elements can be either positive or negative (costs): they are positive whether switching from the configuration set in the matrix rows to a new configuration set in the matrix columns requires an additional investment (e.g. the purchase of an additional resource). On the other hand, the elements of the matrix are negative when the switching between two different configurations requires to disinvest (i.e. to dismiss resources). In the latter case, the value is negative since firm can sell the additional resource and at least partially recover the value.

Switching costs are calculated by solving the following expression (8.7) which compares two configurations in terms of number of available resources in each configuration. By detail, $c_{w,i}$ is the cost to switch from configuration w to a new i. Therefore, it is:

- equal to the investment in purchasing the additional resources of the alternative i when moving from configuration w to i involves more machines;
- equal to the gain from selling the additional resources of the alternative w, when moving from configuration w to i. In this case, it would be reported as a negative value.

Parameters are defined in Table 8.4.

Table 8.4 Model parameters

Parameter	Definition
$AVAIL_{i,s}$	Availability expressed in terms of number of available resources s in the configuration i
IC_s	Investment cost required to purchase an additional unit of resource type s
$gain_s$	Return on investment from selling a unit of resource type s. It is assumed that this share is constant for each resource

The problem has been formulated as follows:

$$\begin{aligned} lc_{w,i} = & \sum_s \left[MAX\left(0, \left(AVAIL_{i,s} - AVAIL_{w,s}\right)\right) \cdot IC_s \right] + \\ & - \sum_s \left[MAX\left(0, \left(AVAIL_{w,s} - AVAIL_{i,s}\right)\right) \cdot IC_s \cdot gain \right], \quad \forall w, i \end{aligned} \tag{8.7}$$

8.6 Sequential Model

The second step of the valuation model is to develop the "Sequential Model". The aim is to optimize the configuration investment trajectory over the time horizon by minimizing the expected cost to reply to the demand scenarios that can randomly arise.

The assumptions for the sequential model are as follows:

- Each performance is associated with a configuration i while each scenario node j is uncertain. In order to represent this uncertainty, it is assumed that three sub-scenarios are possible (index $k = 1, \ldots, 3$):
  - Pessimistic case $b_{i,j,1} = BBase_{j,i} * \theta_1$, with $\theta_1 > 1$;
  - Base (most likely) case $b_{i,j,2} = BBase_{j,i} * \theta_2$, with $\theta_2 = 1$;
  - Optimistic case $b_{i,j,3} = BBase_{j,i} * \theta_3$, with $\theta_3 < 1$;
- Introduction of risk aversion through a discount rate r;
- Introduction of a system ramp-up coefficient to be used every time a new configuration is chosen;
- Introduction of two types of budget constraints to be considered:
  - Budget limit at any time stage;
  - Total budget limit over the all time horizon.

These budget constraints lead the decision maker to choose to switch configuration or to run the legacy one as in the previous time step.

Data are defined in Table 8.5.

The decision variables are reported in Table 8.6.

The problem formulation is as follows:

$$MIN \left\{ \begin{array}{c} \left[\sum_t \sum_j \sum_i \sum_k x_{i,t} \cdot PSS_k \cdot \frac{B_{i,j,k}}{(1+r)^t} \cdot PS_{j,t} \right] + \\ \left[\sum_t \sum_w \sum_i y_{t,w,i} \cdot \left(\frac{C_{w,i}}{(1+r)^t} + \frac{RU\_C_{i,t}}{(1+r)^t} \right) \right] \end{array} \right\} \tag{8.8}$$

The objective function is subject to the following constraints:

$$\sum_i x_{t,i} = 1, \quad \forall t \tag{8.9}$$

Table 8.5 Model data

Data	Definition
$PS_{j,t}$	Occurrence probability for each scenario node j at any time stage t
$C_{w,i}$	Switching costs from configuration w to i. At the start, these costs can be negative (e.g. if the change implies the sale of a resource)
$B_{i,j,k}$	Performance Matrix with sub-scenario k of performance (manufacturing cost) for configuration i in facing scenario node j. The calculation of this parameter was discussed in the previous section
PSS_k	Where $k = 1,...,K$ is the index that runs over the occurrences of each performance (pessimistic case, most likely case and optimistic case)
r	Six-monthly discount rate
Ru_coeff_i	System ramp-up coefficient. We assume that its value is a portion of the performance of a given configuration and that this "penalty" is sustained by the system only for one time bucket (i.e. the first period in which system switches from a configuration alternative w to another, i.e. the new configuration i)
$RU\_C_{i,t}$	Additional cost sustained by the system if the user switches from a configuration w to a new one i at time stage t. This cost is related to the ramp-up associated with the system
$BUDGET_t$	Available budget by the firm at any time stage t
$BUDGET\_TOT$	Total amount of available budget in the firm

$$x_{t,i} \in [0,1], \quad \forall t, i \tag{8.10}$$

$$y_{t,i,w} \in [0,1], \quad \forall t, i, w \tag{8.11}$$

$$y_{i,w,t} \geq x_{t-1,w} + x_{t,i} - 1, \quad \forall t, i, w \tag{8.12}$$

$$RU\_C_{i,t} = \sum_j \sum_k B_{i,t,j,k} \cdot PSS_k \cdot PS_j \cdot Ru\_coeff_i, \quad \forall t, i \tag{8.13}$$

$$\sum_i \sum_w y_{t,w,i} \cdot C_{w,i} \leq BUDGET_t, \quad \forall t \tag{8.14}$$

$$\sum_t \sum_i \sum_w y_{t,w,i} \cdot C_{w,i} \leq BUDGET\_TOT \tag{8.15}$$

The first constraint means that only one configuration is allowed per time stage. The second and third constraints, respectively, mean that both decision variables are binary variables. The third constraint is related to the switching

Table 8.6 Decision variables

Variable	Definition
$x_{i,t}$	Is equal to 1 if configuration i is selected at time t, 0 otherwise
$y_{t,i,w}$	Is equal to 1 if at time stage t system is switched from configuration w to a new configuration i, 0 if at time stage t there is no switch from a configuration to another one (i.e. index i is equal to w)

variable: it is equal to 1 if index i – that is the configuration selected at time stage t – is not equal to w – i.e. the configuration used at the previous time stage (t-1). The fourth constraint is related to the worsening performance, expressed in terms of increasing cost associated with configuration i arising from the ramp-up coefficient for a new configuration. This cost is sustained only when system switches from configuration w to a new alternative i (i.e. the value of switching variable $y_{t,i,w} = 1$). Finally, the latest two constraints are related to the firm budgetary availability, respectively, at any time stage and over the all time horizon.

8.7 Model Testing

This section describes an experimental run on the valuation model and an analysis applied to budget, outsourcing cost and system ramp-up parameters.[3] The purpose is to show how the model works and what results it returns when some parameters are modified. The model testing has been run on a five year time horizon with a half-year time step – therefore it comes with ten time buckets.

The process starts from the Static Model that receives the information about the set of scenario nodes (in a form of scenario tree, Fig. 8.5) – that has been elaborated internally by the system user – and the set of alternative configurations – that has been elaborated by the machine tool builder. This latter comes

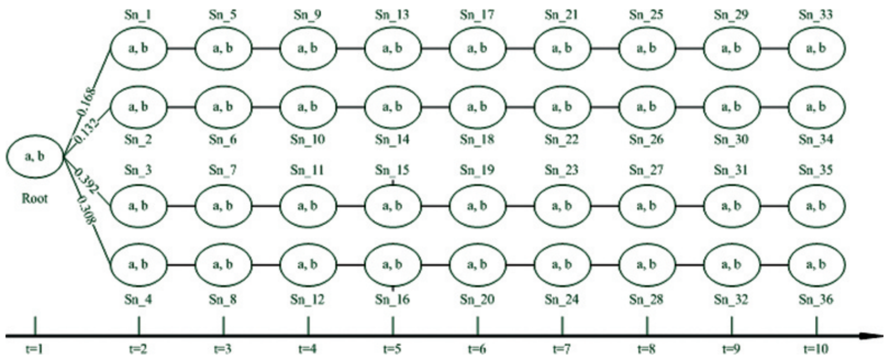

Fig. 8.5 Scenario tree pattern

[3] The model has been written, performed and validated with the Lingo Solver software (version 7.0). Microsoft .NET Framework 2.0 configuration, Microsoft Visual Studio 2005, and Microsoft Office Access 2003 have been used to develop user interfaces and run all the modules in close integration with the modules described in other chapters of the book. The final application has been run on a PC with an Intel Pentium M 740, 1.73 GHz CPU; 512 MB memory.

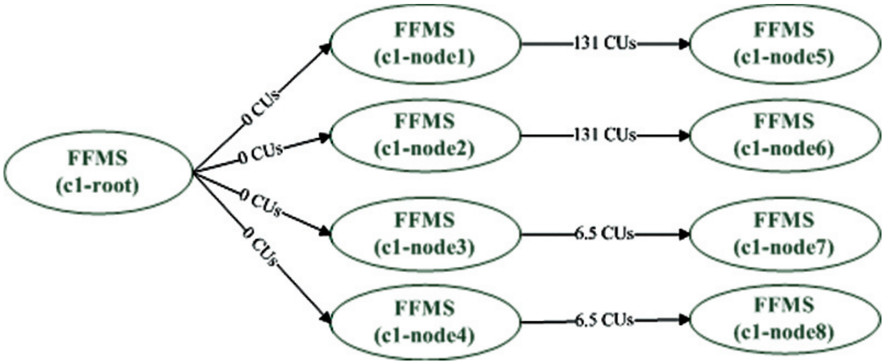

Fig. 8.6 Configuration tree pattern

as a tree as well ("configuration tree", Fig. 8.6) and shows the reconfiguration path laid out by the machine tool builder.

Figure 8.5 shows the scenario tree elaborated by the system user. Each scenario node is a production problem expressed in terms of part mix (the current example includes two part types in the mix: part type "a" and part type "b") and part type volumes. Table 8.7 reports part type volume details deriving from the scenario tree as Fig. 8.5 shows. The first column reports all the scenario nodes starting from the root and progressively numbering all the further ones – that are expressed as "sn_1", "sn_2", etc.

Table 8.7 Part type volumes

Scenario node	Part type "a" volumes [units]	Part type "b" volumes [units]	Scenario node	Part type "a" volumes [units]	Part type "b" volumes [units]
Root	4000	4000	Sn_18	4668	4000
Sn_1	4168	4000	Sn_19	4668	4000
Sn_2	4168	4000	Sn_20	5000	4000
Sn_3	4134	4000	Sn_21	5000	4000
Sn_4	4134	4000	Sn_22	4800	4000
Sn_5	4334	4000	Sn_23	4800	4000
Sn_5	4334	4000	Sn_24	5168	4000
Sn_6	4268	4000	Sn_25	5168	4000
Sn_7	4268	4000	Sn_26	4800	4000
Sn_8	4500	4000	Sn_27	4800	4000
Sn_9	4500	4000	Sn_28	5334	4000
Sn_10	4400	4000	Sn_29	5334	4000
Sn_11	4400	4000	Sn_30	4800	0
Sn_12	4668	4000	Sn_31	4800	0
Sn_13	4468	4000	Sn_32	5500	4000
Sn_14	4534	4000	Sn_33	5500	4000
Sn_15	4534	4000	Sn_34	4800	0
Sn_16	4834	4000	Sn_35	4800	0
Sn_17	4834	4000	-	-	-

Figure 8.6 shows the configuration tree developed by the machine tool builder. The values on the arcs are the investment to be sustained to move from a configuration to another one (expressed in terms of Cost Units). Each configuration involves some resource types and a number of resources per type. Table 8.8 reports the machine and carrier resources characterizing the FFMS configurations at each node. Values and variable names have been simplified to be read more easily.

Column "Rhs" in Table 8.8 refers to the capacity constraint for each type of resource that is the right-hand side of the expression (8.3) while left-hand side defines the time required by each part type to be produced by each resource. Tables 8.9 and 8.10 report this last information.

Considering the set S of part mix scenario nodes as Table 8.7 shows, with $S \in \{s_1, s_2, \ldots, s_j, \ldots, s_{37}\}$, and the set C of configurations illustrated in Table 8.8, with $C \in \{c_1, c_2, \ldots, c_i, \ldots, c_9\}$, the Static Model returns the performance value of configuration c_i under the scenario node s_j for each set $\{s_j, c_i\}$. The performance value comes from solving the minimum cost optimization problem defined by the expression (8.1). According to its formulation, the Static Model returns the cost of using a system configuration to produce as much internally as it is allowed by its capacity constraints and outsourcing the unsaturated demand quote (refer to expressions (8.4) and (8.5)). The Static Model returns the switching costs per configuration couple as well. According to Sect. 8.5.2, switching costs are calculated by solving the expression (8.7) which compares two

Table 8.8 Features per configuration

Node	Configuration	Type of resource	Number of resources	Rhs
Root	FFMS (c1-root)	Carrier 01	1	5142.89
Root	FFMS (c1-root)	Machine 07	1	7200
1	FFMS (c1-node1)	Carrier 01	1	5142.85
1	FFMS (c1-node1)	Machine 07	1	7200
2	FFMS (c1-node2)	Carrier 01	1	5142.85
2	FFMS (c1-node2)	Machine 07	1	7200
3	FFMS (c1-node3)	Carrier 01	1	5142.85
3	FFMS (c1-node3)	Machine 07	1	7200
4	FFMS (c1-node4)	Carrier 01	1	5142.85
4	FFMS (c1-node4)	Machine 07	1	7200
5	FFMS (c1-node5)	Carrier 01	1	5142.85
5	FFMS (c1-node5)	Machine 02	1	7200
5	FFMS (c1-node5)	Machine 07	1	7200
6	FFMS (c1-node6)	Carrier 01	1	5142
6	FFMS (c1-node6)	Machine 02	1	7200
6	FFMS (c1-node6)	Machine 07	1	7200
7	FFMS (c1-node7)	Carrier 01	1	5142.85
7	FFMS (c1-node7)	Machine 07	1	7200
8	FFMS (c1-node8)	Carrier 01	1	5142.85
8	FFMS (c1-node8)	Machine 07	1	7200

Table 8.9 Working time and cost per configuration (part 1)

Part type	Configuration	Resource	Working time	Working cost
A	FFMS (c1-root)	Carrier 01	0.013	0.667
A	FFMS (c1-root)	Machine 07	0.093	4.615
A	FFMS (c1-node1)	Carrier 01	0.013	0.667
A	FFMS (c1-node1)	Machine 07	0.092	4.615
A	FFMS (c1-node2)	Carrier 01	0.013	0.667
A	FFMS (c1-node2)	Machine 07	0.092	4.615
A	FFMS (c1-node3)	Carrier 01	0.013	0.667
A	FFMS (c1-node3)	Machine 07	0.092	4.615
A	FFMS (c1-node4)	Carrier 01	0.013	0.667
A	FFMS (c1-node4)	Machine 07	0.092	4.615
A	FFMS (c1-node5)	Carrier 01	0.018	0.889
A	FFMS (c1-node5)	Machine 02	0.033	1.657
A	FFMS (c1-node5)	Machine 07	0.028	1.395
A	FFMS (c1-node6)	Carrier 01	0.018	0.889
A	FFMS (c1-node6)	Machine 02	0.033	1.657
A	FFMS (c1-node6)	Machine 07	0.028	1.395
A	FFMS (c1-node7)	Carrier 01	0.013	0.667
A	FFMS (c1-node7)	Machine 07	0.092	4.615
A	FFMS (c1-node8)	Carrier 01	0.013	0.667
A	FFMS (c1-node8)	Machine 07	0.092	4.615

Table 8.10 Working time and cost per configuration (part 2)

Part type	Configuration	Resource	Working time	Working cost
B	FFMS (c1-root)	Carrier 01	0.012	0.625
B	FFMS (c1-root)	Machine 07	0.080	4.013
B	FFMS (c1-node1)	Carrier 01	0.012	0.625
B	FFMS (c1-node1)	Machine 07	0.080	4.013
B	FFMS (c1-node2)	Carrier 01	0.012	0.625
B	FFMS (c1-node2)	Machine 07	0.080	4.013
B	FFMS (c1-node3)	Carrier 01	0.012	0.625
B	FFMS (c1-node3)	Machine 07	0.080	4.013
B	FFMS (c1-node4)	Carrier 01	0.012	0.625
B	FFMS (c1-node4)	Machine 07	0.080	4.013
B	FFMS (c1-node5)	Carrier 01	0.012	0.625
B	FFMS (c1-node5)	Machine 02	0.00	0.00
B	FFMS (c1-node5)	Machine 07	0.080	4.013
B	FFMS (c1-node6)	Carrier 01	0.012	0.625
B	FFMS (c1-node6)	Machine 02	0.00	0.00
B	FFMS (c1-node6)	Machine 07	0.080	4.013
B	FFMS (c1-node7)	Carrier 01	0.012	0.625
B	FFMS (c1-node7)	Machine 07	0.080	4.013
B	FFMS (c1-node8)	Carrier 01	0.012	0.625
B	FFMS (c1-node8)	Machine 07	0.080	4.013

Table 8.11 Investment costs per resource type

Type of resource	Investment cost (cost units)
Carrier 01	30.97
Machine 02	131.00
Machine 07	187.00

configurations in terms of number of available resources per configuration. The needed information are included by Table 8.8 (i.e. in "Number of resources" column) while Table 8.11 contains the information about the investment required by each machine and carrier resources.

Next, the second step of the Valuation Model is the Sequential Model, whose structure has been presented by Sect. 8.6 of this chapter. It receives both the performance and the switching costs matrixes as inputs from the Static Model, and the information about the occurrence probability for each scenario node that are from the scenario tree pattern (Fig. 8.5). Moreover, it receives the budget availability and the discount rate for each time stage t, as illustrated in Table 8.12.

The Sequential Model outcome is the optimal evolution of the system over the planning horizon and derives from solving the minimum cost optimization problem illustrated in expression (8.8). Table 8.13 shows the outcome.

Considering that the starting configuration is FFMS (c1-root), the model suggests that the optimal choice be to switch at time stage $t = 1$ from configuration FFMS (root-c1) to FFMS (Reconfiguration-c1-5) and keep on with this configuration over the entire planning horizon.[4] Switching from FFMS (root-c1) to FFMS (Reconfiguration-c1-5) comes with a required investment (131.00 CUs)[5] and is possible since the budget constraint (expression 8.14) at time stage $t = 1$ is satisfied.[6] The final total cost related to this choice is 63734.43 CUs.[7]

Table 8.12 Budget constraints and discount rates for each time stage

Time	1	2	3	4	5	6	7	8	9	10
Budget	2000	3000	4000	2000	3000	5000	6000	5600	10000	2300
Rate	2	3	4	5	6	2	3	2	1	12

[4] Outsourcing costs for both products of the mix are equal to 1300 CUs.

[5] In fact, by making a comparison between the two configurations (i.e. FFMS (root-c1) and FFMS (Reconfiguration-c1-5)), an additional type of resource "Machine 02" (see Table 8.9) is present in the new configuration FFMS (Reconfiguration-c1-5). Its investment cost is equal to 131.00 CUs, as illustrated in Table 8.11.

[6] In fact, the investment cost related to configuration FFMS (Reconfiguration-c1-5) is 131.00 CUs and is lower than budget the availability at time stage $t = 1$, i.e. 2000 CUs (see Table 8.12).

[7] System value is calculated as the sum of discounted performance values over the planning horizon.

Table 8.13 System planning over 10 time stages

Time stage	Optimal configuration
1	FFMS (Reconfiguration-c1-5)
2	FFMS (Reconfiguration-c1-5)
3	FFMS (Reconfiguration-c1-5)
4	FFMS (Reconfiguration-c1-5)
5	FFMS (Reconfiguration-c1-5)
6	FFMS (Reconfiguration-c1-5)
7	FFMS (Reconfiguration-c1-5)
8	FFMS (Reconfiguration-c1-5)
9	FFMS (Reconfiguration-c1-5)
10	FFMS (Reconfiguration-c1-5)

A sensitivity analysis has been performed on budget constraints, outsourcing costs and system ramp-up coefficients, varying just one of them and keeping the others out of the run. Results are worthy to see how the model – and the final outcomes – reacts to some parameter modifications.

The budget parameter has been varied as first: a new stream of budget constraints has been set as illustrated in Table 8.14 – that is setting budget to zero at the first time stage.

Based on this budget, the firm is not able to change the system configuration at the first time stage and therefore is forced to keep on with the starting configuration unless there is a no switching cost configuration. The new output is shown in Table 8.15:

Considering that the starting configuration is FFMS (root-c1), it means that the optimal choice is to switch, at time stage $t = 1$, from configuration FFMS (root-c1) to FFMS (Reconfiguration-c1-2), and given that it is the same as FFMS (root-c1) (refer to Tables 8.8, 8.9 and 8.10), the switching comes for free. At time stage $t = 2$ the model leads to switch from configuration FFMS (Reconfiguration-c1-2) to FFMS (Reconfiguration-c1-6) (where the investment required is 131.00 CUs) and to keep on with this configuration over the entire planning horizon. This switching is possible since budget availability at time stage $t = 2$ is equal to 3000 CUs. The system cost related to this new choice is 65840.15 CUs. It is higher than the first case (i.e. 63734.43 CUs) because, at time stage $t = 1$, the selected configuration is FFMS (Reconfiguration-c1-2) whose performance is greater (i.e. greater manufacturing costs) than the FFMS (Reconfiguration-c1-5) one.

A second run has been performed by setting all the budget constraints to zero as Table 8.16 illustrates below. In this case, it is expected to keep on with the same configuration over the all time horizon or, at last, to switch towards a free

Table 8.14 Zero budget at time 1

Time	1	2	3	4	5	6	7	8	9	10
Budget	0	3000	4000	2000	3000	5000	6000	5600	10000	2300

Table 8.15 System planning over 10 time stages – zero budget case at $t = 1$

Time stage	Optimal configuration	Time stage	Optimal configuration
1	FFMS (Reconfiguration-c1-2)	6	FFMS (Reconfiguration-c1-6)
2	FFMS (Reconfiguration-c1-6)	7	FFMS (Reconfiguration-c1-6)
3	FFMS (Reconfiguration-c1-6)	8	FFMS (Reconfiguration-c1-6)
4	FFMS (Reconfiguration-c1-6)	9	FFMS (Reconfiguration-c1-6)
5	FFMS (Reconfiguration-c1-6)	10	FFMS (Reconfiguration-c1-6)

switching system configuration otherwise the budget constraint in expression 8.14 would not be satisfied.

The new output related to this situation is illustrated in Table 8.17:

As expected, the Sequential Model returns the same configuration over the entire planning horizon. Considering that the starting configuration is FFMS (root-c1), this means that the optimal choice is to switch, at time stage $t = 1$, from configuration FFMS (root-c1) to FFMS (Reconfiguration-c1-4) due to zero switching costs. The final total cost related to this new solution is 75748.55 CUs and is higher than the first two cases because there are more tightened constraints. It is worth showing that, as soon as the budget constraint turns to be positive sometime on the horizon,[8] for instance at time stage $t = 5$, the model would suggest that the user switches towards a lower costly configuration. Indeed, if the available budget at time stage 5 is 3000 CUs, the model points out to switch to the solution FFMS (Reconfiguration-c1-5) as it costs only 131.00 CUs, and to keep on with it as further time steps are again limited by a zero budget. In this case, the total system cost would be 69444.37 CUs that is lower than the no budget case at all.

Sensitivity analyses have been then performed on the outsourcing cost parameter. The expected outcome must be a total cost trend such as in Fig. 8.7. Considering outsourcing costs on x-axis and total costs on y-axis, and considering a fixed part mix quantity to produce, total costs are directly proportional to outsourcing costs until these last ones are equal to internal costs. From the break even cost point on, total costs decrease their slope given that are made of internal costs up to the capacity constraints and outsourcing cost to cover the unsaturated demand.

Table 8.16 Zero budget at all time stages

Time	1	2	3	4	5	6	7	8	9	10
Budget	0	0	0	0	0	0	0	0	0	0

[8] Budget availability must be also larger than the investment required by switching towards a new higher performance configuration (i.e. lower manufacturing costs).

Table 8.17 System planning over 10 time stages – zero budget case at all time stages

Time stage	Optimal configuration	Time stage	Optimal configuration
1	FFMS (Reconfiguration-c1-4)	6	FFMS (Reconfiguration-c1-4)
2	FFMS (Reconfiguration-c1-4)	7	FFMS (Reconfiguration-c1-4)
3	FFMS (Reconfiguration-c1-4)	8	FFMS (Reconfiguration-c1-4)
4	FFMS (Reconfiguration-c1-4)	9	FFMS (Reconfiguration-c1-4)
5	FFMS (Reconfiguration-c1-4)	10	FFMS (Reconfiguration-c1-4)

The sensitivity analysis has been applied by considering both the unbounded[9] and bounded capacity cases, and confirmed the expected results. In the first case, outsourcing costs have been varied from 700 CUs up to 1300 CUs with a 10 CU-step and total costs varied according to a positive first derivative and a negative second derivative. Results are graphically shown in Fig. 8.8.

When outsourcing costs are equal to 950 CUs, total costs stop to increase because the breakeven point has been reached for both part types *a* and *b*, and the entire production is accomplished internally. Zooming in on the breakeven area, it is worth highlighting that internal manufacturing machineries for part type *a* become cost-effective from 939.42 outsourcing CUs on while for part type *b* from 946.38 CUs on. As Fig. 8.9 shows below by zooming in on these points, the slope of total cost function changes twice according to a double internal-external costs matching.

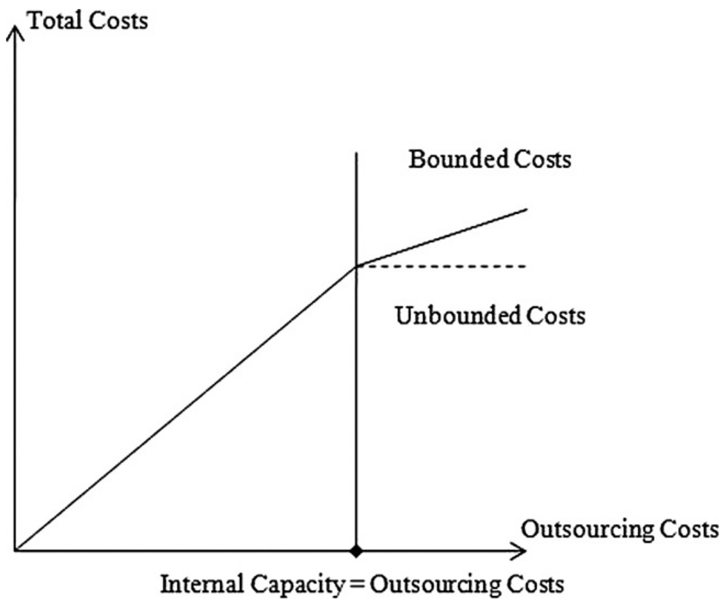

Fig. 8.7 Total cost vs. outsourcing costs

[9] It has been rendered by setting a large manufacturing capacity.

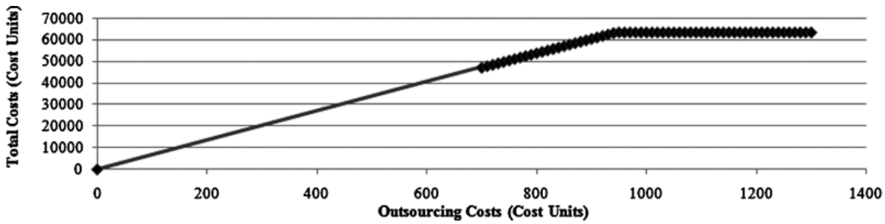

Fig. 8.8 Sensitivity analysis on outsourcing costs (unbounded capacity)

In the second case, it has been assumed that the configuration FFMS (c1-root) was available by setting an end-less ramp-up coefficient for the other configurations: the analysis has been run on an up to 2000 CUs range and results are as shown in Fig. 8.10. When outsourcing costs 946.38 CUs, it becomes more cost-effective to produce part type *b* internally and it does the same for part type *a* when outsourcing passes 1252.82 CUs. From this point on (named *B* on Fig. 8.10), total costs continue to increase because the internal system is not capable to process all the demand, and the residual demand quote is given outside the firm.

Sensitivity analysis has finally been run on the system ramp-up coefficient that is the additional cost that a new configuration entails during the launching phase. It has been quantified as a percentage of the total cost performance of a new system or its reconfiguration, and is considered just for the first time stage by which the system is introduced. All previous model runs adopted a system ramp-up coefficient equal to 0.1. By varying it, the switching path can change over the time period because the final outcome changes. The analysis has been performed by assuming that only three system configurations are available.[10]

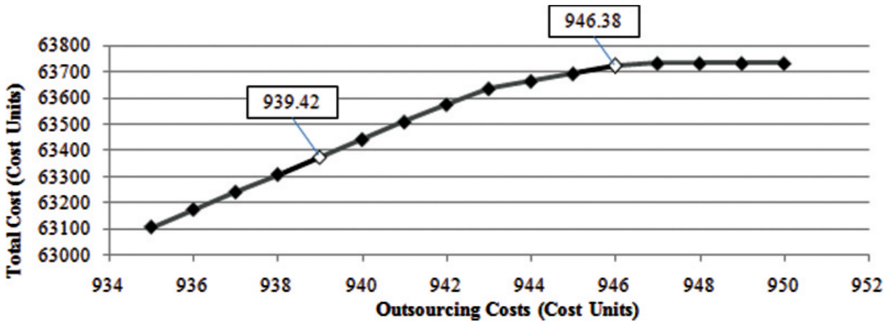

Fig. 8.9 Sensitivity analysis on outsourcing costs – zooming in (unbounded capacity)

[10] This simplification is due to the fact that FFMS (Reconfiguration c1-1), FFMS (Reconfiguration c1-2), FFMS (Reconfiguration c1-3) and FFMS (Reconfiguration c1-4) are equivalent to FFMS (root-c1) while FFMS (Reconfiguration c1-5) is equivalent to FFMS (Reconfiguration c1-6) and FFMS (Reconfiguration c1-7) is equivalent to FFMS (Reconfiguration c1-8) (see Tables 8.8, 8.9 and 8.10).

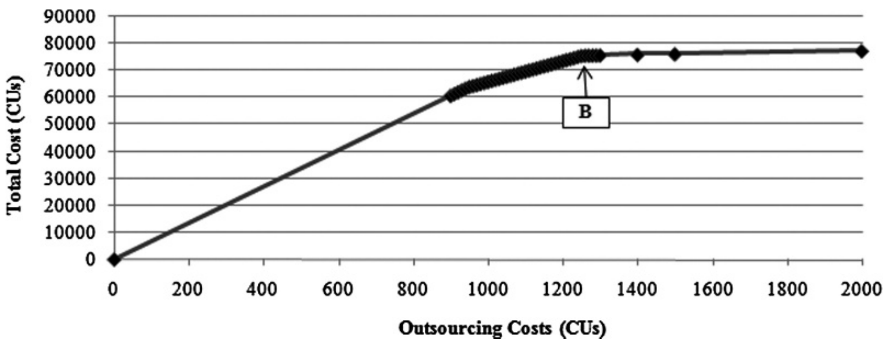

Fig. 8.10 Sensitivity analysis on outsourcing costs (bounded capacity)

FFMS (c1-root), FFMS (Reconfiguration c1-5) and FFMS (Reconfiguration c1-7).[11] Then, it has been assumed that the ramp-up coefficient is null for both configurations FFMS (c1-root) and FFMS (Reconfiguration c1-7) while outsourcing costs are equal to 1300 CUs so that producing internally is cheaper than outsourcing for both part types. Launching the model returns the FFMS (Reconfiguration c1-5) as the optimal solution because related internal costs are the lowest (Table 8.18).

Next, the model has been launched on different ramp-up coefficients in order to have a major insight into the effects on the final system performance – that is always formalized in terms of total costs. The final solution sensitivity has been measured by varying the coefficient from 0 to 2 by a 0.1 step. Figure 8.11 shows the total cost function trend when the FFMS (Reconfiguration c1-5) ramp-up coefficient increases. Looking at Fig. 8.11, from 0 to 1.6, the total cost increases and the optimal system solution is FFMS (Reconfiguration c1-5) over the entire horizon. From 1.6 on, at time $t = 1$ and $t = 2$ the optimal configuration is (c1-root) while from the third time stage on it turns to be FFMS (Reconfiguration c1-7).

The same analysis has been accomplished by working on the ramp-up coefficient for FFMS (Reconfiguration-c1-7)[12] and results are shown in Fig. 8.12.

Table 8.18 Internal cost for both part types of the mix

Part type	FFMS (c1-root)	FFMS (Reconfiguration c1-5)	FFMS (Reconfiguration c1-7)
a	1252.81	939.42	1252.81
b	946.4	946.4	946.40

[11] As seen previously in this section, this is possible supposing an endless ramp-up coefficient related to the other configurations.

[12] Please, remember that in Fig. 8.11 the ramp-up of FFMS (Reconfiguration c1-7) was null. In Fig. 8.12 ramp-up of FFMS (c1-root) is always null and ramp-up of FFMS (Reconfiguration c1-5) is 1.6.

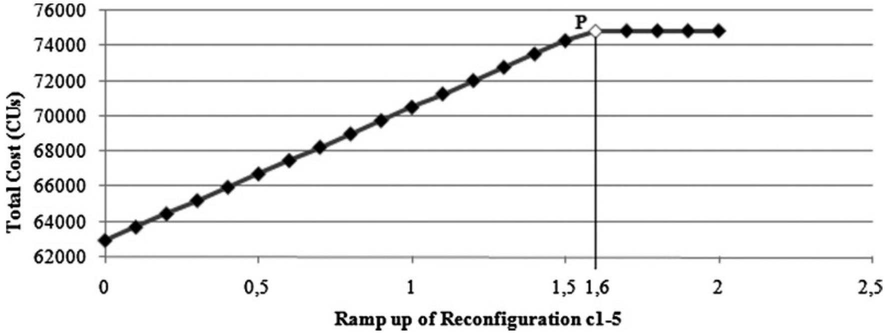

Fig. 8.11 Total cost vs. ramp-up of configuration FFMS (Reconfiguration c1-5)

In this case, total costs grow when the ramp-up coefficient for FFMS (Reconfiguration c1-7) grows up to P^I. At point P^I, the ramp-up coefficient of FFMS (Reconfiguration c1-7) is so high that the model suggests selecting FFMS (c1-root) over the entire planning horizon. From point P^I on the total cost function does not depend on the ramp-up coefficient of FFMS (Reconfiguration c1-7) anymore and is equal to 74868.87 CUs.

Results from this model are of course limited by its simplicity. However, the sensitivity analysis on three main parameters – budget constraint per time stage, outsourcing costs and system ramp-up coefficient – laid out some performance curves that are consistent with the expected results. Due to this empirical evidence, the valuation model as has been developed in this chapter is valid and reliable, and can be used to solve manufacturing system life-cycle planning problems, including those real-world parameters that strongly affect the decision-making process.

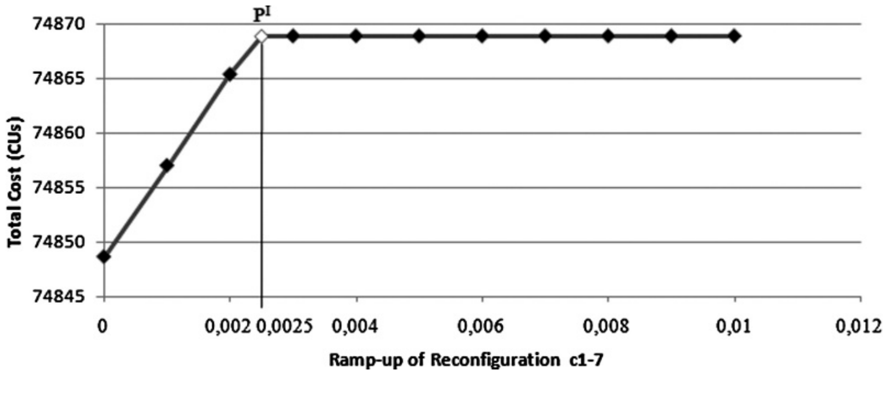

Fig. 8.12 Total cost vs. ramp-up of configuration FFMS (Reconfiguration c1-7)

8.8 Conclusions

According to previous sections, this chapter tackled the problem for a system user of planning the manufacturing system life-cycle over a given medium-term horizon. As Chap. 2 showed, the empirical evidence made clear that manufacturing small to medium-sized firms are in trouble when have to deal with machine tool builders in defining, negotiating and purchasing the manufacturing system that includes the flexibility and capacity degree they are looking for. Some misalignments between machine tool builder's and system user's perspectives usually tend to make both players to convey to a final solution that is not optimal for both. In addition, due to some inefficiency within the user organization – i.e. operational decisions are not aligned to and consistent with strategic decisions – the system user is often not satisfied by the decision because it is not exactly what he/she wanted and/or is not capable to execute it. In turn, this can lead to losing either profitability or demand.

Using the valuation model that has been presented in the current chapter, the system user can make some breakthroughs as it holds an easy-to-use tool to assess and plan a manufacturing system investment. By using it, the user can assess a single solution and find out how much further upgrades would cost or can compare several bids from different machine tool builders or, once more – as it is assumed in this chapter – it can handle a more complex situation where the machine tool builder draws up a multi-solution commercial bid. This valuation model would be then useful to better appreciate the focused flexibility concept embedded in some manufacturing solutions, by interactively observing the effects of alternative solutions that differ with respect to switching costs and manufacturing performance.

In the end, some further developments are pointed out to improve this model and its applicability to the entrepreneurial world. It should be investigated how to introduce dynamic programming methodologies in order to handle more complex problems, i.e. a broader part mix, a major granularity for time steps, more potential decisions. In terms of contents, it should be investigated how to adapt the "Real Option" concept to the problem complexity and find the acceptable trade-off between reality approximation and simplicity of results. As known, the mentioned approaches to the problem are interesting and also aligned with most of the scientific studies in this field. However, the problem of overcoming their computational and usability complexity still must be solved and hindered their diffusion among manufacturing entrepreneurs so far.

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Chapter 9
System Performance Simulation and Analysis

Antonio Grieco and Francesco Nucci

Abstract The performance evaluation of different system architectures and the development of tailored methods to manage FFMSs at operational level are the final decision activities of the design approach presented in this book. In this chapter a simulation theory-based tool is presented. The proposed tool is able to automatically simulate a set of different scenarios and to provide the necessary capability to compare the performance of FFMSs versus FMSs. Moreover, tailored methods to optimize the performance at operational level are introduced in the simulated supervisor of the FFMSs architecture. The methods allow to split the execution of the part program among different machining centers and to manage the opportunity to share more than one pallet transport system on the same route. The methods are validated through simulation experiments.

Keywords Discrete event simulation · Performance evaluation · Focused flexibility manufacturing systems – FFMS

9.1 Introduction to Manufacturing Systems Modeling

This chapter introduces the different steps to develop a general tool based on simulation theory for the performance evaluation of FFMSs. Given the characteristics of the FFMS paradigm and the goal of comparing different solutions in terms of architecture and configuration, a very flexible simulation tool is necessary. Using this tool it is possible to test the goodness of the solutions proposed in Chap. 7 and related to systems characterized by focused flexibility, in comparison with alternative configurations belonging to the general paradigm of flexible manufacturing systems.

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Simulation is a wide known tool in the manufacturing field in order to assess system performance, see McHaney (1991), Pidd (1998) and Robinson (2004). There are numerous paradigms and tools which are capable of modeling various aspects of a system at different levels of detail. The problem of modeling new paradigms of production systems has been widely discussed in literature as reported by Averill et al. (2000), Zeigler et al. (2000), Banks et al. (2005), Lu and Wong (2007), Ryan and Heavey (2006) and Park (2005).

In particular, simulation studies of process flow analysis in industrial plant have been investigated by Sivakumar and Chong (2001), Wohlgemuth et al. (2006) and Siemiatkowski and Przybylski (2006). Moreover, system configuration studies have been performed in order to select the most suitable resource allocation as addressed by Gien and Jacqmart (2005), Creighton and Nahavandi (2003) and Greasley (2008). Finally, various works deal with the FMS configuration problem in order to exploit the flexibility property in production systems (Toma et al. 1995; Tolio et al. 2001).

The innovative aspect of the proposed work stands in the specificity of the systems considered as object of evaluation. It is important to notice that some characteristics of the focused flexibility systems, as reported in Cantamessa et al. (2007), have a great impact on the evaluation of system performance. Indeed the features concerning the FFMS configuration phase (see Chap. 7) will have to be effectively exploited within the simulation experimental campaign. Moreover, the FFMS solutions will be compared to the FMS solutions in order to evaluate the real benefits coming from customizing the system flexibility on the production requirements. This calls for an in-depth analysis of operative techniques for the resolution of scheduling problems on focused flexibility systems. Indeed, it is necessary to develop effective operational policies in order to fully exploit the features of the system architectures under analysis. For this reason, on the one hand, new methods and models suitable for FFMSs have been developed for the operational production management at the scheduling level. On the other hand, results available in the literature are included in the simulation models for traditional FMS systems.

One important result of this chapter is that, by means of the developed simulation models, it will be possible to quantify the impact of flexibility on system performance. In order to fulfill such a necessity, two important issues have to be considered and introduced in the evaluation tool.

First, the need of flexibility in a manufacturing system arises from the stochastic and dynamic nature of the operating environment. Sources of uncertainty are changes in demand (e.g. part types and part-mix) and resource availability (e.g. machine downtimes). In the proposed framework, all these features have been considered to develop a tool for the evaluation of the different architectures over different hypothesized scenarios.

Second, different types of flexibility may be combined to provide different levels of performance for the considered manufacturing system. Consequently, the value of the aggregate flexibility cannot be straightforwardly obtained by combining the measures of its component flexibilities. In the proposed framework, the evaluation of the different production architectures will be made taking into account the concept of aggregate flexibility via appropriate simulation models. Simulation tools are able to simulate the different configurations obtained as an input from the methods developed in Chap. 7. The design of the simulation experiments is affected by the output obtained from Chap. 8 where the production capacity acquisition plan is defined for the FFMS and for the FMS, under a certain set of economic and financial parameters.

In the following section, a formal representation of the systems under study and the corresponding simulation model are introduced. In Sect. 9.3 the simulation model is validated taking into consideration a case study addressing the relationship between flexibility issues and system performance. Since the details of the system architectures under comparison may significantly influence the final results, the description of each single element considered in the simulation model assumes an important role. For this reason, the simulation model requires a formal description of the elements and of their interrelations which have been presented in Sect. 9.3. The formal model has been the basis for the implementation of the simulation one. In order to guarantee the features of generality and intelligibility to the formal model, the UML language has been adopted.

At the end conclusions related with the tool validation phase are given.

9.2 Description of the Simulation Model Building Phases

The goal of this chapter is to present the design of an environment for the evaluation of manufacturing systems in which flexibility features are relevant. The specific goal is the comparison between two system architectures. The first system is designed according to the focused flexibility paradigm while the second deals with the classical idea of flexible manufacturing systems.

Since in the evaluation of flexible manufacturing systems, the impact of rules and methods at the operational level is remarkable, it will be necessary to include in the evaluation tool all the rules designed to manage both the part and tool flows in the system. Moreover, in order to realize in an efficient way the validation phase, illustrated in the following chapter, the proposed tool has a library of management rules. The tool may be configured to evaluate different scenarios and alternatives in an automatic way. The automatic integration of different management rules according to the constraints and to the characteristics of the system have been preliminary solved.

In order to realize an efficient tool for the requirements of the validation phase, discrete event simulation has been selected among the applicable methods. Discrete event simulation allows to analyze a production system and to assess the relative performance, even if the preliminary activity related with the representation of the system model is a remarkable task. Indeed, the accuracy of the results obtainable from the simulation tool depends on the soundness of the model adopted to represent the system.

Various techniques and languages are available to describe systems through formal representation. Moreover, several software packages may be exploited to write simulation software on the basis of system formal representation. In Anglani et al. (2002) an approach to integrate the formal representation phase and the development of a simulation model is presented. The proposed methodology is based on the UML standard and on the simulation language Arena. The authors exploit the UML capabilities to represent the significant components and relationships of a flexible manufacturing systems even if the proposed model is a simplified representation of the actual FMS complexity.

Therefore, considering the advantages given by the use of UML standard language, the formal models of FFMS and FMS architectures reported in this book have been formalized UML language. In particular, the first step in order to realize the proposed tool is to represent the system at the desired level of detail. Second, the simulation model has to be developed. Third, the validation and verification phases have to be carried out as usually done for a generic software package. A characterization of the system to be reproduced is reported in the following sub-sections.

9.2.1 Simulation Model Formalization

The description of the simulation model has the objective of illustrating each component at the desired level of detail with a high level of generality and intelligibility. In order to accomplish this goal, it is necessary to select a formal language to describe the model with the required features. As previously reported, the language exploited in the following is the Unified/Universal Modeling Language (UML). This language consists of a set of object-oriented modeling notations that have been standardized by the OMG object management group in order to represent every kind of system. It defines a meta-model based on a graphical notation that can be used as a support for formal modeling. The UML uses graphical notations to illustrate all the system specifications. Since specifications are usually complex, there are several diagrams, refereed as UML diagrams, available to provide different views of the analyzed system. UML diagrams represent three different views of a system model: the functional requirements view, the static structural view and the dynamic behavior one.

The representation of the components and relationship of the system under study is reported in the following. The UML use-case and activity diagrams will be the basis of the simulation model. The following section provides a deeper insight into the single system components and synthetic comments to the diagrams. The most relevant UML use cases are reported in Fig. 9.1, Tables 9.1 and 9.2.

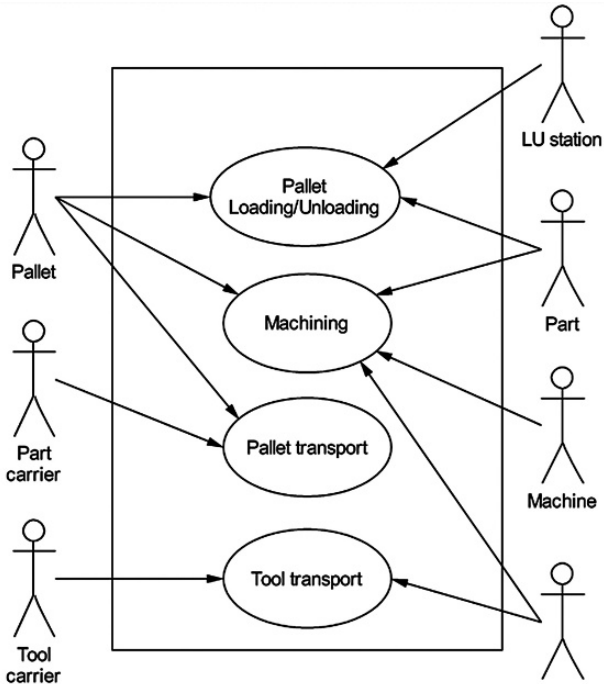

Fig. 9.1 Use case of the main activities of the simulation model

A complete UML representation is not reproducible in this chapter because of the complexity of the system. For this reason, a global illustration has been provided with the aim of referring to the most significant UML modules. Anyway, the proposed representation refers to the model of an automated production system dedicated to machining operations of the

Table 9.1 Actors of the main activities of the simulation model

Actor	Description
Pallet	A hardware interface between the load/unload station and the machines which allows that parts are processed in the system.
Part	A raw or partially machined part to be processed.
Part carrier	A transport system dedicated to move pallets among the machining centers and the load unload stations.
LU station	A LU station dedicated to load/unload parts from and to the pallet.
Machine	A machining center (general purpose or dedicated) on which pallets are processed.
Tool	A tool used in machining operations.
Tool Carrier	A carrier dedicated to transport tools among the tool magazines of machining centers and the system central tool magazine.

Table 9.2 Description of the activities of the simulation model

Activity	Description
Pallet loading and unloading	Parts are loaded and unloaded on/from a pallet by the LU station unit.
Machining	A pallet loaded with raw or partially machined parts is processed by a machining center with a proper set of tools.
Pallet transport	A pallet is moved from a machine to another machine or to a LU station (and vice versa).
Tool transport	A tool is moved from a machine to another machine or to the Tool Room (and vice versa).

parts. Such a model is characterized by a set of flexibility features related with the management of the machining operations. These features have been designed in order to evaluate the performance of both FFMS and FMS architectures.

A first flexibility characteristic regards the possibility to process the parts on one or more machines. This means that each part may require one or more setup to be completely machined. As anticipated in Chap. 7, parts are mounted on pallets by means of fixtures. It is possible to associate more than one pallet to each part in each different setup. Each pallet may be loaded with one or more parts in different setup positions. Moreover, pallets are moved among the Load/Unload (LU) station and the machining centers by an automatic part transport system. On each machining center, the pallet processing is executed with a proper set of tools. Tools can be shared among the machining centers. Once a pallet is completely machined, it returns to the Load/Unload (LU) station in order to unload, partially or completely, processed parts and to load raw parts.

In the developed simulation model it is assumed that machining centers and the Load/Unload stations are laid out over a line and that the Load/Unload stations are centrally located with respect to the machining centers.

The activity diagram related to the transition of the pallet from the LU station to a machining center is shown in Fig. 9.2, Tables 9.3 and 9.4.

The processing of a pallet on a machining center is represented on the related activity diagram reported in Fig. 9.3, Tables 9.5 and 9.6.

The unloading of the pallet is represented by the activity diagram reported in Fig. 9.4, Tables 9.7 and 9.8.

9.2.2 Implementation of the Simulation Model

Since several different configurations, for each system architecture, have to be simulated, a key-point is the implementation of an evaluation environment able to be automatically configured both from the physical and from the logical

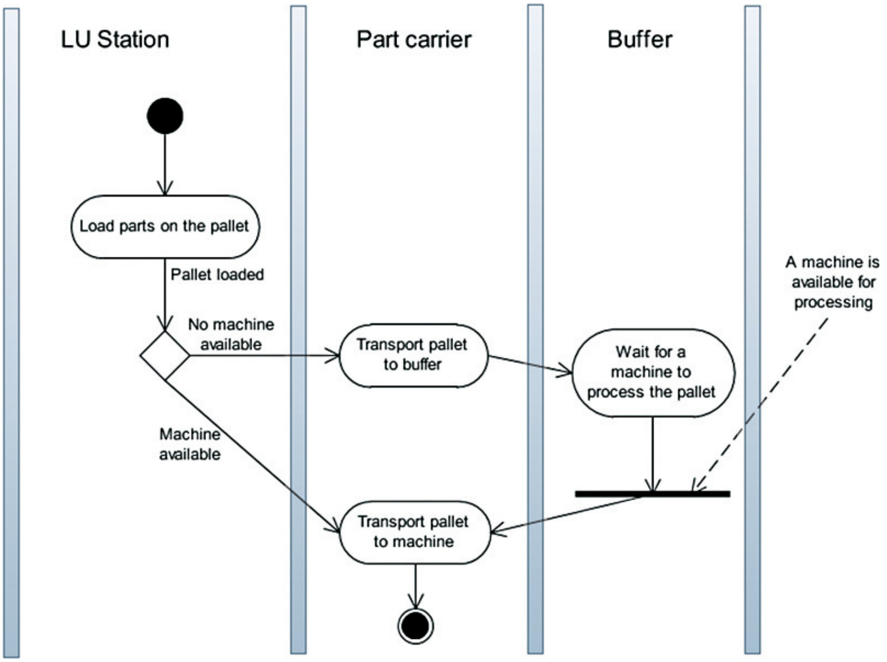

Fig. 9.2 Activity diagram of the "pallet loading" activity of the simulation model

Table 9.3 Sub-activities related to the "pallet loading" activity

Sub-activity	Description
Load parts on the pallet	All the parts required by each pallet are loaded at the LU station.
Transport pallet to buffer	Moves a pallet waiting for a machining center to a buffer.
Transport pallet to machine	A pallet is transferred to a machining center in order to start the processing phase.
Wait for a machine to process the pallet	Each pallet waits for a free machining center in order to start the necessary processing.

Table 9.4 Decisions related to the "pallet loading" activity

Decision	Description
No machine available	The pallet does not find an available machining center for being processed.
Machine available	Since an idle and admissible machining center is available in the system, the pallet is transferred to the machining center to be processed.

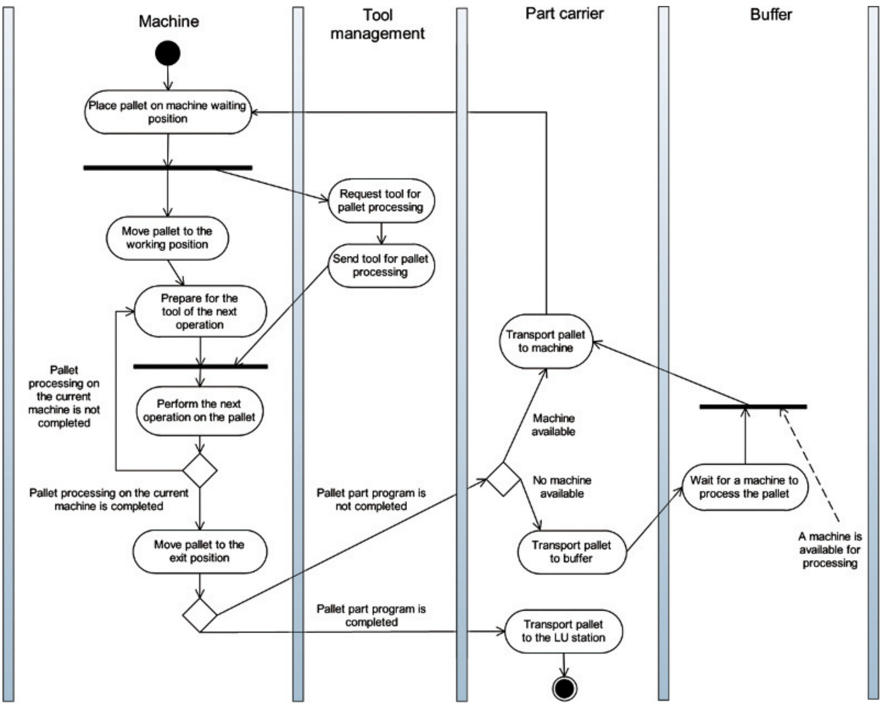

Fig. 9.3 Activity diagram for the "pallet machining" activity of the simulation model

point of views. The developed simulation model allows to simulate automatically different scenarios on the same configuration and to switch between different simulation campaign automatically.

The configuration of the simulation model is enabled by varying a specific set of model parameters. It is important to notice that even the management policies can be modified by varying the proper set of parameters. The generality of the simulation model allows users to reproduce a Focused Flexibility Manufacturing System in addition to a general Flexible Manufacturing System.

The FFMSs/FMSs system configurations that might be simulated are a combination of the following resources and parameters. In particular, it is important to note that the simulation model may be configured both in the number of the resources available in the system (e.g. the total number of machining centers) and in the functional parameters of system resources. The complete list is reported in the following:

Table 9.5 Sub-activities related to the "pallet machining" activity

Sub-activity	Description
Place pallet on machine waiting position	A pallet enters into the machining center and occupies the waiting position of the machining center.
Move pallet to working position	A pallet occupies the working position of the machining center.
Prepare for the tool of the next operation	The supervisor of the machining center searches the tool for the next operation.
Request tool for the pallet processing	The next tool is requested by the tool management system. If the tool is not present into the machining center magazine, the tool management system requests the tool from the central magazine or from another machining center.
Send tool for the pallet processing	Once the necessary tool arrives at the machining center, the tool is loaded in the local tool magazine.
Perform the next operation on the pallet	If the necessary tool is present, the next operation is performed by taking into account both the cutting time and the total time of the operation.
Move pallet to the exit mode	A pallet is moved from the processing position of the machining center to the waiting position.
Transport pallet to machine	If the part program of a pallet cannot be completed on the current machining center, the pallet is moved to another machining center; different classes of machining centers may be considered.
Transport pallet to LU station	If a pallet part program is completely executed, an unloading operation is necessary.
Transport pallet to buffer	A pallet is moved to a buffer to wait for an available machining center.
Wait for a machine to process the pallet	At the buffer, a pallet waits for a machine in order to be free to start the necessary processing.

Table 9.6 Decisions related to the "pallet machining" activity

Decision	Description
Pallet processing on the current machine is completed	A pallet has completed the set of operations that may be performed on the current machining center.
Pallet processing on the current machine is not completed	A pallet requires other operations on the current machining center (which in turn requires different tools).
Pallet part program is completed	A pallet has completed the set of the operation to be performed (all the part program), therefore an unloading operation must be performed.
Pallet part program is not completed	A pallet requires other machining operations to be performed on a different machining center or machining centers; it requests to be moved to another machining center.
No machine available	A pallet which does not find an available machine in order to be processed is moved to the buffer.
Machine available	The pallet is transferred to the available machine.

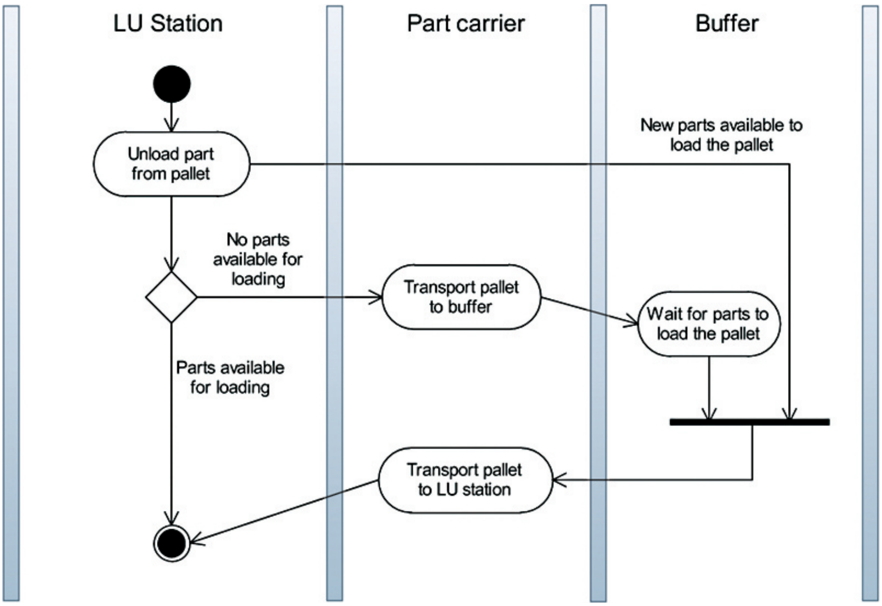

Fig. 9.4 Activity diagram related to the "pallet unloading" activity of the simulation model

Table 9.7 Sub-activities related to the "pallet unloading" activity

Sub-activity	Description
Unload parts from pallet	All the parts loaded on a pallet are unloaded at the LU station and are available for other operations if necessary.
Transport pallet to buffer	The pallet is moved to a buffer to wait for parts to be loaded.
Transport pallet to LU station	A pallet is transferred to the LU station in order to be loaded with new available parts.
Wait for parts to load the pallet	At the buffer, the pallet waits for parts to be loaded.

Table 9.8 Decisions for the "pallet unloading" activity

Decision	Description
No parts available for loading	Since no parts can be loaded on the pallet, the loading operation is not executed.
Parts available for loading	Since parts to be loaded on the pallet are available, the pallet can be loaded.

- up to *N_max* machining centers over a line layout, with *N_max* = 8;
- a loading / unloading station centrally positioned in the line layout;
- a transport system to handle pallets into the system, consisting of one or two shuttles able to transport a single pallet and equipped with an automated exchange system;
- up to *P_max* pallets buffer places distributed along the line layout, with *P_max* = 50;
- a central tool magazine distributed along the line layout;
- a tool room for tool regeneration;
- a tool transport system. The tool transport system moves on a straight track; it connects the central tool magazine with the tool magazine of each machining center;
- each machine is equipped with a tool magazine provided by a tool exchange system and a pallet exchange system between the workstation and the pallet transportation system.

On the basis of the assumptions previously reported, an example of system layout is reported in Fig. 9.5. Moreover, each system resource requires the definition of a list of parameters, as explained in the following.

The machining centers are placed in line along the path of the carrier according to an assigned distance and are characterized by the following parameters: machine type, shuttle rotation time, size of the tool machine magazine and time for tool change.

For each part type, it is necessary to define the following parameters: the part type code, the number of parts to be produced, and the code of the first pallet type occupied by the parts. Indeed, any part may be associated with only one pallet type, if only one setup is required to completely machine the considered parts. Otherwise, the part type may be associated with a set of different pallet types when more than one setup is needed. In such a case, the sequence of pallets associated with each part type and to each part setup has to be defined.

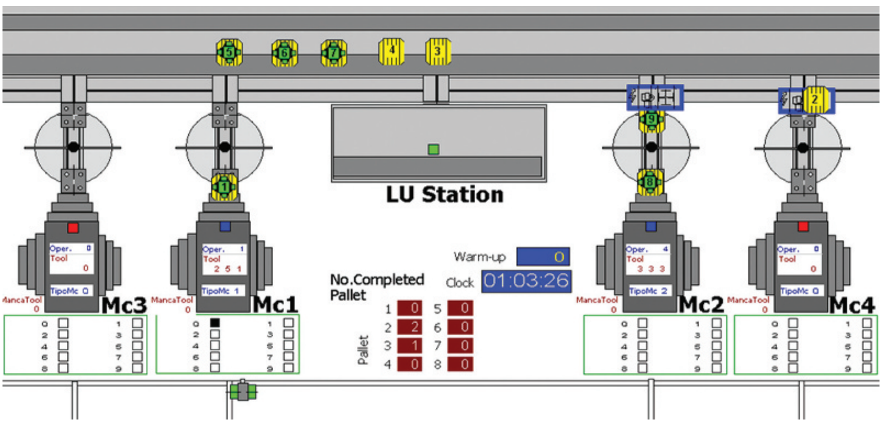

Fig. 9.5 System layout of the simulation model

The part program is defined by specifying the part type related, the list of machining operations, the tool type per operation, the cutting time, the rapid time and the association of the operation to the machine type.

With regard to the part carrier, it is possible to set the following parameters: the average speed, the time required to load and unload the pallets to and from the carrier and the management policy to manage the transportation requests.

The tool carrier is characterized by the following parameters: average speed and loading and unloading time.

The simulation model can manage different tool types. For each tool type the following parameters have to be defined: the tool type code, the number of copies per tool type, the regeneration time and the tool life.

Once all the system resources with the corresponding set of parameters have been defined, it is necessary to complete the assumption for the simulation model by defining the part and tool management policies that must be considered in each specific simulation experiment. The various options for the two management policies are described in the following.

9.2.2.1 Pallet Management Policy

Parts move along the system by means of the pallet transport system. In the case of multiple requests for the pallet carrier, different management policies can be adopted:

- Policy 1. First In First Out (FIFO) rule. Requests are ordered on the basis of the instant they are issued.
- Policy 2. For each pallet i, a priority index is calculated on the basis of the quantity:

$$\alpha_i = \mathrm{ProcessedPallets}_i / \mathrm{PalletsToBeProcessed}_i \qquad (9.1)$$

where α_i is related to the percentage of part type machined. The lower is the value of α_i, the higher is the priority of the corresponding pallet i.

- Policy 3. For each pallet i, a priority index is calculated on the basis of the quantity:

$$\beta_i = \mathrm{ProcessedPallets}_i / (\omega_i \mathrm{PalletsToBeProcessed}_i) \qquad (9.2)$$

where

$$\omega_i = \mathrm{PalletProcessingTime}_i / \max(\mathrm{PalletProcessingTime}_i) \qquad (9.3)$$

The last policy is similar to the second policy but the time to process the remaining pallets is considered with the weight ω_i. The higher is the processing time of a pallet i, the lower is the parameter β_i, the higher is the priority for the pallet i.

Once the carrier is loaded, the transport mission is executed and the pallet is carried to the first idle machining center; if this is not possible it is the pallet is loaded on the first machine with a free waiting position or in the worst case it will be stored in the pallet buffer. A pallet management module coordinates the transport system in order to satisfy as soon as possible to transport requests.

If the number of tool carrier in the simulation experiment is equal to one, the main goal of the pallet management module is to avoid idle time of the machining centers for lack of pallets. This main goal is satisfied taking into account also the possibility to minimize the total length of the paths necessary to the pallet transport system to execute the requested missions. Otherwise, if the total number of part transport systems is greater than one, the describe part management problem is augmented in the complexity for the necessity to manage also the route of the transport systems in order to avoid deadlock situations.

9.2.2.2 Tool Management Policy

The tool management policy implemented in the simulation model, see Toma et al. (1995), allows the machining centers to share each different tool copy available in the system. When a pallet reaches the machining center waiting position, the tools which executes such a set of operations, as defined in the part program, are requested. As soon as a tool completes the processing on a machining center, it is available for other machining operation even on other machining centers. Indeed, if a machining center needs a tool that is not present in its local magazine, firstly, a request to the central magazine is generated. If a copy of the requested tool type is not available, a request is generated towards the tool magazines of the machining centers. Tool requests are ordered on the basis of FIFO rules. As soon as a machining center releases a tool copy, the first tool request is selected. If a tool copy matching the tool request is available, a tool mission is scheduled to move the tool to the machining center. Otherwise, the availability of tools belonging to the tool requests list is checked tool by tool until the list is empty. The list of scheduled tool transport missions is re-defined each time a tool copy is released by a machining center in order to limit idle time on the machining centers due to tool unavailability. When the tool life ends, the tool copy is transferred to the tool room for the regeneration process and it is not available for booking.

9.2.3 Focused Flexibility Aspects in the Simulation Model

Focused Flexibility Manufacturing System configurations can be simulated by the described simulation model by properly setting the corresponding parameters. In order to extract such information, the simulation model has to access to the data contained in the main database tables described in Chap. 4. In this section, the relationships between the simulation model data and the main database tables will be described.

9.2.3.1 Model Data Definition

The main parameters of a simulation run (length, warm-up, number of replications) are inferred from a specific table of the database named "simulation" (Table 4.27). Information about Machines, LU station, Tools and Carriers are extracted considering the concepts of Tables 4.8, 4.9, 4.10 and 4.11 together with their relations reported in Table 4.22.

In the simulation model, potentially each part program may be executed on different machining centers. Consequently, a pallet can perform the first set of operations on a specific machining center, and then move to a different machine type to execute other processing operations. In order to collect the necessary information, in the simulation model, the part program is defined according to the concepts of "Workingstep" (Table 4.16) and "Workplan" (Table 4.17). In this way the part program associated with the "pallet" is completely determined. The remaining parameters associated with the "Pallet" concept are extracted from the information connected to Workpiece and Scenario (Table 4.1, 4.3, 4.17, 4.18, 4.21 and 4.23).

9.2.3.2 FFMS Model Management Aspects

Since the constraint to perform all the operations related to each setup on a single machining center may be relaxed in FFMS architectures, several machining centers may be involved in the processing of a single pallet for each setup. For this reason, a greater number of transportation requests may be issued by each pallet during the part program processing than in the FMS case. Indeed, in the FFMSs architecture in addition to the transportation missions among the LU station, the machining centers and the pallet buffer positions, it is possible to move a pallet among many machining centers. This could lead to select more than one pallet carrier for the transport system. Therefore, the evaluation of the performance of production systems characterized by more than one pallet carrier becomes critical.

In the proposed simulation model, it is foreseen the possibility of simulating the FFMS configuration with two pallet carrier units sharing the same railway. However, in FFMSs the need to move pallets directly among different machining centers could lead to collision problems when two carriers are present. For this reasons, a pallet management system dedicated to the FFMS architecture has been designed and implemented in the simulation model.

Also in the FMS architecture it is possible to design two transport units. However, this type of configuration is usually adopted splitting the transport path in two separate and independent zones (e.g. the left and the right side respect to the LU station). This configuration may be considered collision-free.

Anyway, the pallet management system determines the sequence of pallet missions and schedule the activities of the transport systems. In the simulation model an attribute "release time" is related to each transport mission. It represents the time in which the pallet requires the transport mission. The transport mission is labeled “critical” if the mission scheduling leads starvation or blocking for one resource (machining centers or LU stations). The critical time for a mission represents the maximum time within the relative transport mission need to be satisfied in order to minimize the resources idle or lack of pallets. The policy to select the next mission to be executed by the carriers, among the set of equivalent missions, may consider:

- balancing the machine/LU station resource utilization,
- optimizing the performance of the transport system.

The first aspect takes into account the resource state in order to select the next pallet to be moved. A policy can select the next mission depending on the release time or the critical time. The second aspect considers the departure and arrival stations of a mission in order to optimize the carrier path. Various alternatives are implemented in the simulation model. The “most critical mission” policy selects the mission in order to balance the machines/LU station saturation. The “transport system optimization” policy selects the mission in order to optimize the transport system performance. Moreover, a hybrid approach has been implemented. Taking into account the time windows of each transport missions and the performance of the transport systems, it is possible to selects a set of equivalent missions respect to the goal to minimize resources idle time. The hybrid policy considers the equivalent set and selects the next mission in order to optimize the transport system (N is a policy parameter). In this way, even if the optimization of the transport system is restricted to a limited number of missions (the most critical ones), it is possible to introduce optimization policy of the pallet transport system.

In the simulation model, if two carriers are considered, each time a carrier has to start the execution of a mission, a deadlock has to be avoided with the second part carrier. For such a reason, the transport path can be modified in order to avoid deadlocks and a carrier can be forced to wait the end of another transport mission. The order and the paths by which the missions of the two part carrier are executed depends on the mission attributes. The pallet carrier unit movements may be in conflict when a carrier is on the other carrier path. Deadlock may occur if carriers move along the same railway segment in different directions. A specific logic has been implemented to avoid deadlocks. The proposed solutions are reported in the following. On the one hand, it is foreseen that a carrier seizes the entire railway portion before the execution of the related transport mission. On the other, a carrier has to be moved away from the path that has to be seized by the other carrier; in such a case a carrier is moved along a different and longer path than the shortest one.

The described features related with the FFMS architecture implemented in the simulation model has been validated through a set of simulation experiment described in the following paragraph.

9.3 The Simulation Model Validation

The simulation model testing usually is a long task due to the necessity to take into consideration both the verification and validation phases. This section aims at evaluating the behavior of FFMS solutions in output from the FFMS design approach. A specific case study has been defined in order to execute the validation of the simulation model. This phase aims at validating the following characteristics:

- ability of simulating different cases in which bottlenecks may be identified either in the general purpose machining centers or in the dedicated ones;
- ability of simulating a two part carrier system case; the part carriers must be able to share the same railway.

The proposed case study may be summarized as follows. The FFMS configuration is composed of four CNC machining centers: the first three machining centers are general purpose while the other one is a dedicated machining center. The dedicated center is the closest to the LU station, which is centrally located within the in-line layout.

The machine tool change time is 2.5 s. The shuttle rotation time is 6 s. No machine failures are supposed to occur. The pallet transport system may be configured up to two part carriers; its main features are: linear speed 45 m/min and pallet load time 15 s. For the validation phase the hypothesis is made that only one lot has to be produced. Each part has to be completely processed on the same pallet if both the general purpose and the dedicated machining center are used. Each pallet is loaded with four parts.

At the LU station, four working units are available for the load and unload operations. The load/unload time is 10 min for pallet. The total number of operations to completely machine the considered part is 15. For each operation, the cutting time comes from a uniform distribution with min/max values equal to 0.8 min and 1.6 min; once inferred, such numerical values are used for all the experimental campaign. For each operation, the total time is 20% longer than cutting time.

The part program is supposed to be divided into three general parts: GP1, DED and GP2. The first group of operations, refereed as GP1 in the following, is constrained to be executed on a general purpose machining working center. The second group, DED, represents the central portion of the part program that is constrained to be processed on the dedicated machining resource. Finally, the last group, GP2, is executed on a general purpose machine. In general terms, the production cycle is: GP1/DED/GP2. For example, if the cardinality of the total number of operations in the group DED is equal to one, the operations from 1 to 6 and from 8 to 15 are executed by just one of the general purpose machine; whereas the operation 7 is executed by the dedicated machine. The total number of tool types is 15. For each tool type, 4 copies are available. Since the simulation experiment is deterministic, only one replication is performed. The warm-up period length is 600 min, whereas the replication length is 7200 min.

9.3.1 Numerical Results

In order to evaluate the behavior of the FFMS solution in comparison to the FMS architectures, the validation phase has been carried out focusing the analysis on the following factors:

- **D**: number of operations of the part program that are executed on the dedicated machine (DED) with respect to the total number of operations in the part program. In particular, this value is varied from 1 to 7.
- **R**: part program reduction factor. The part program length is investigated by reducing the initial duration of the operations. For each operation, both the cutting time and the total time are reduced by the factors: 1 and 10;
- **C**: number of pallet carriers, in the value set {1, 2}.

  The system performance is evaluated in terms of:
- average general purpose machines utilization, referred as "Av GP Mc Util" in the following table,
- average dedicated machine utilization, refereed as "Av Ded Mc Util" in the following table,
- average transport system utilization, considering the overall carrier system and referees as "Av Transport system Util" in the following table,
- average pallet throughput, refereed as "Av Throughput" in the following table and measured in pallets per hour unloaded from the system,
- average mission rate, refereed as "Av MissionsRate" in the following table and measured in missions per hour.

The obtained results are reported in Table 9.9.

The first set of experiments (A1–A4) aims at demonstrating the possibility of splitting the execution of the part program on different machining centers and evaluating the different bottlenecks in the systems (parameter D is varied). In the simulation R/D/C = 1/1/1 the utilization of the general purpose machining centers is equal to 1 whereas the dedicated machining working center utilization is equal to 0.27. On the contrary, in the simulation R/D/C = 1/7/1 the utilization of the general purpose machining centers is equal to 0.62 while the dedicated machining working center utilization is equal to 100%. If the D value is set to 3 or 5, the machine workload is almost balanced. Indeed, three general purpose machining centers deals with (15–D) operations, whereas the general purpose machining center performs the remaining D processing operations. Therefore, the optimal D value may be inferred from the equation 3/1 = (15-D)/D, that is D = 3.75. Consequently, the best throughput among the simulated tests is obtained for D = 3 (R/D/C = 1/3/1). The simulation test cases with R = 1 and

Table 9.9 Numerical case study results for the analysis of the FFMS performance

Exp	R	D	C	Av GP Mc Util	Av Ded Mc Util	Av Transport system Util	Av Throughput [pallets/h]	Av MissionsRate [missions/h]
A1	1	1	1	1.00	0.27	0.10	0.89	3.57
A2	1	3	1	1.00	1.00	0.12	1.03	4.10
A3	1	5	1	1.00	1.00	0.10	0.83	3.31
A4	1	7	1	0.62	1.00	0.07	0.60	2.38
B1	1	1	2	1.00	0.27	0.05	0.89	3.57
B2	1	3	2	1.00	1.00	0.06	1.03	4.10
B3	1	5	2	1.00	1.00	0.05	0.83	3.31
B4	1	7	2	0.62	1.00	0.03	0.60	2.38
C1	10	1	1	1.00	0.26	1.00	8.27	33.09
C2	10	3	1	1.00	1.00	1.00	8.68	34.72
C3	10	5	1	1.00	1.00	1.00	7.74	30.94
C4	10	7	1	0.61	1.00	1.00	5.91	23.65
D1	10	1	2	1.00	0.27	0.89	8.92	36.74
D2	10	3	2	1.00	1.00	1.00	10.07	41.02
D3	10	5	2	1.00	1.00	0.78	8.23	33.50
D4	10	7	2	0.62	1.00	0.46	5.95	24.21

C = 1 confirm the validity of the proposed model, reproducing the same results in terms of bottleneck shift between the general and the dedicated machining centers.

The second set of experiments (B1–B4) aims at proving the possibility to simulate different configurations increasing the total number of part carriers (parameter C is varied to 2). The increasing of the number of part carriers from 1 to 2 is not justified from a performance standpoint. The overall transport system utilization decreases by a factor of 2 because of the second carrier. Taking into consideration the total number of carrier missions per hour with two part carriers, the total number of missions is equal to the previous one. The same result is obtained for the pallet throughput and machine utilization. Briefly, the second carrier is not necessary in case R = 1.

The third set of experiments (C1–C4) considers the decrease of the part program length by a factor of 10 and the exploitation of only one part carrier (R = 10 and C = 1). In this way, the transportation request rate increases significantly. The utilization of machines is equivalent to the R = 1 case. However, the transport system represents the system bottleneck. Indeed, the pallet throughput is not decupled respect to the R = 1 case, in particular in the simulation experiment with R/D/C = 1/3/1.

In the last set of experiments (D1–D4) a second carrier is added and the system performance increases. The second carrier allows in order to significantly improve the pallet throughput when D = 3 is considered. Indeed, since the machining centers workload is balanced, the second carrier allows exploiting the machine set. In this case, production rate increases of 16% (from 8.68 to 10.07 pallet/h). On the contrary, if R/D/C = 10/7/1 and R/D/C = 10/7/2 are considered, the second carrier is not exploited (from 5.91 to 5.95 pallet/h) because the main bottleneck is represented by the dedicated machine.

Finally, it is possible to argue that the number of the allocated carriers is important when the number of transportation requests increases. Indeed, if there is not a part program reduction, each pallet remains on machines for a long period and the second carrier unit is not necessary. Indeed, when the part program length decreases, the second carrier unit allows increasing the overall number of transport missions. Since the carrier units share the same path, the presence of the second unit leads to increase the number of collisions between transport requests. For such a reason, it is important exploiting the second carrier unit only when the transportation request rate is significant.

9.4 Conclusions

In this chapter a simulation model capable of evaluating various FFMS configurations has been presented. In particular, the modeling phase has been reported focusing on the key characteristics of the considered systems. The simulation model has been validated in order to demonstrate the influence of the flexibility issues on system performance. Moreover different cases exist in which such production architecture is suitable to be adopted. Further development could regard a deep investigation of the relationship between flexibility and performance. Some analyses have been presented in the last chapter of this book referring to a real production case in order to establish the potential of FFMS architecture in the foreseeable future.

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Chapter 10
Testing

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Abstract This chapter aims at presenting the experimental analyses carried out to evaluate the benefits coming from applying the manufacturing system design framework presented in the previous chapters. To this purpose three families of products belonging to different production contexts have been studied. These products have been used as input data of the testing experiments which were aimed at studying the performance of an FFMS when facing production problems characterized by technological and demand evolution. The testing experiments have been carried out by exploiting the software tools that have been developed by implementing the methodologies presented in the previous chapters.

Keywords FFMS design framework testing · Design of Experiment · Value of the Stochastic Solution · System Performance Evaluation

10.1 Introduction

In the previous chapters of this book, the main phases of an FFMS design approach have been described to provide a structured guidance to determine the system characteristics which better fit the production requirements. Despite each single chapter investigates a specific aspect of the system design process, the analysis of production problems represents a common feature of strategic importance. Indeed, the ability to customize the production system characteristics on the input requirements determine economic advantages as well as system solutions that can better cope with future changes of the demand (Cantamessa et al. 2007).

These advantages regard both machine tool builders and system users. On the one hand, the strategy of customizing the system flexibility on the production

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requirements provides benefits to the machine tool builders because the reduction of manufacturing system costs can be exploited to enhance the profit margin and/or to increase the competitiveness in the market by offering cheaper solutions (see Chap. 1). On the other hand, the system user is particularly interested in purchasing an affordable system designed considering both the present and the forecasted production problems. The industrial interest on the topic of focused flexibility has been addressed in Chap. 2 by means of an empirical investigation. Moreover, some industrial efforts in the direction of customizing system solutions on the customer needs have been presented in Chap. 3.

Anyway, in practice most of the designed system can still be classified in the family of traditional systems despite these architectures do not represent an optimal solution. This is partly due to the absence of approaches to support machine tool builders when facing the main steps of the manufacturing system design.

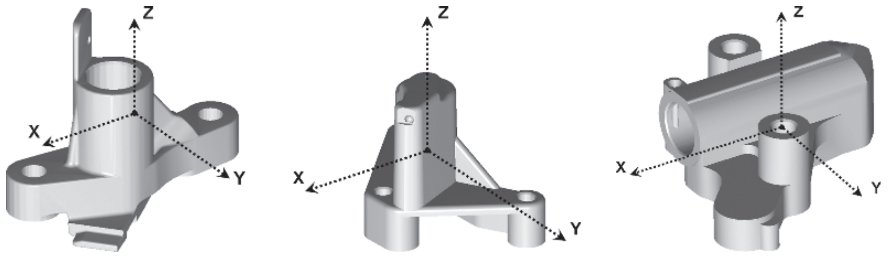
The aim of this chapter is to show that there is a set of production problems which would require customized system solutions. The first part of this chapter presents an analysis of three different families of products which have been used to test the FFMS design approach. The second part of the chapter will be dedicated to show the most relevant results obtained from the testing experiments. In particular, the experiments aim at addressing the robustness of system solutions with respect to the variability of the production problems. Moreover, the benefits coming from using the stochastic programming technique for designing the system have been evaluated. Finally, the viability of the designed system solutions is analyzed through simulation.

The testing experiments carried out in this chapter complete the analyses already presented in Chap. 7 where the impact of the production problem characteristics (i.e. the part family, the part mix and the aggregate demand) and of the database of selectable resources (i.e. cost and performance of the dedicated machines) on the performance of Focused Flexibility Manufacturing Systems has been investigated. This chapter is structured as follows. Section 10.2 analyzes the families of products while Sect. 10.3 describes how the test cases have been generated. Then, Sects. 10.4, 10.5 and 10.6 present the results of the testing experiments.

10.2 Description of the Product Families

In this section three different families of products will be presented. These families are composed of:

- products for automotive applications;
- products for railway applications;
- products used in the field of flow control systems.



(a) (b) (c)

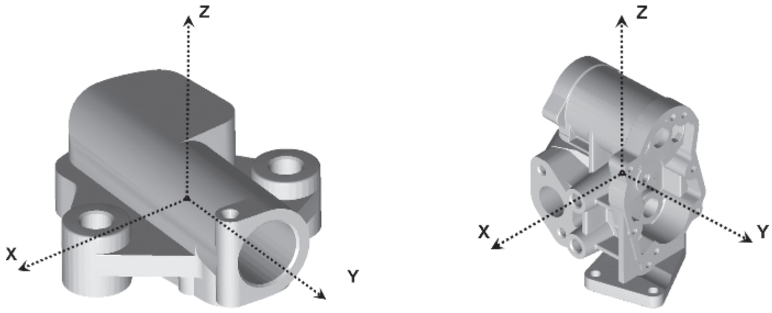
Fig. 10.1 (**a**) Product code 240 (**b**) Product code 260 (**c**) Product code 270

In particular, the first and third families are composed of products of mid technological complexity, whereas the second one includes complex part types. All the analyzed products can be processed on horizontal machining centers since they are characterized by prismatic features. However, this does not strictly mean that the geometry of the products is prismatic: for instance, the last family of products produced for hydraulic applications is composed of axial-symmetric part types.

Information related to the described families of products have been formalized using the framework presented in Chap. 4.

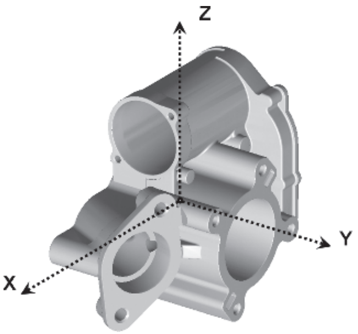
10.2.1 Automotive Components

The products composing this first family are automotive components of a hydraulic primary chain tensioner, i.e. a hydraulic actuator which constantly keeps the chain in tension. The part family is composed of seven workpiece types (product codes 240, 260, 270, 280, 380, 500 and 900). For each part type a 3D drawing is shown in the Figs. 10.1, 10.2 and 10.3.

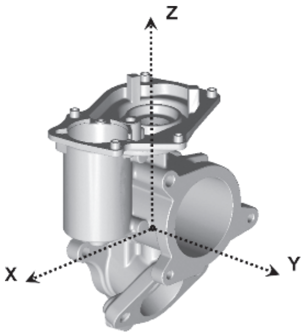


(a) (b)

Fig. 10.2 (**a**) Product code 280 (**b**) Product code 380



(a)



(b)

Fig. 10.3 (**a**) Product code 500 (**b**) Product code 900

The material and the bounding geometry (i.e. a parallelepiped) of each workpiece type is reported in Table 10.1. Information is formalized following the definition of Workpiece type introduced in Chap. 4 (see Sect. 4.3.1 and Table 4.1). In particular, all the analyzed products are in aluminum alloy and the dimensions of the products is measured referring to a coordinate system with the origin placed in the center of each bounding geometry.

Once the information concerning the part family has been collected, each workpiece type has been analyzed from a technological point of view. In particular, the working directions have been defined as represented in Figs. 10.4, 10.5 and 10.6.

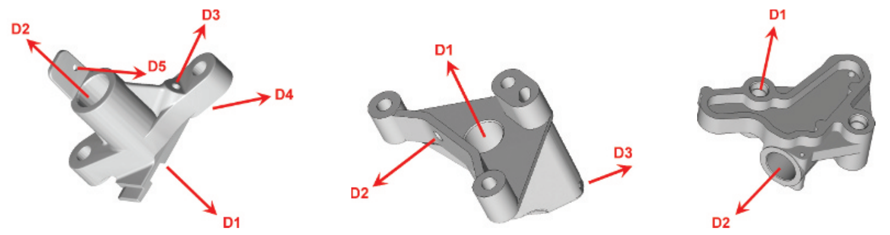
Data regarding the description of the machining features and the machining operations are reported in the following tables. As an example, the machining features of the product code 280 are illustrated in Fig. 10.7.

Tables 10.2, 10.3, 10.4, 10.5, 10.6, 10.7, 10.8 and 10.9 report the data concerning the machining features following the definitions provided in Table 4.2 of Chap. 4. Each table includes data related to the position of the machining feature (coordinates *x*, *y* and *z*) and the working directions expressed as direction cosines (*cos_x*, *cos_y*, *cos_z*).

Table 10.1 Characteristics and dimensions of the workpiece types

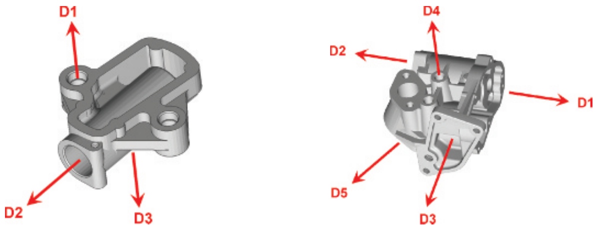
id_workpiece	its_material	x_pos	x_neg	y_pos	y_neg	z_pos	z_neg
240	Aluminum alloy	33.95	−33.95	18.23	−18.23	27.16	−27.16
268	Aluminum alloy	22.45	−22.45	36.9	−36.9	24.75	−24.75
270	Aluminum alloy	32.98	−33	33.75	−33.75	13	−13
280	Aluminum alloy	28.7	−28.7	30.95	−30.95	11.4	−11.4
380	Aluminum alloy	41.59	−41.59	55.42	−55.42	57.13	−57.13
525	Aluminum alloy	64.48	−64.48	37.8	−37.8	59.3	−59.3
916	Aluminum alloy	64.56	−64.56	45.2	−45.2	83.81	−83.81

x_pos = x_bounding_pos; x_neg = x_bounding_neg; y_pos = y_bounding_pos; y_neg = y_bounding_neg; z_pos = z_bounding_pos; z_neg = z_bounding_neg



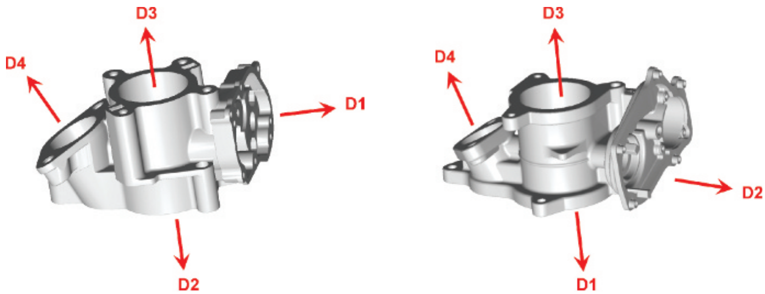
(a) (b) (c)

Fig. 10.4 Working directions (**a**) Product code 240 (**b**) Product code 260 (**c**) Product code 270



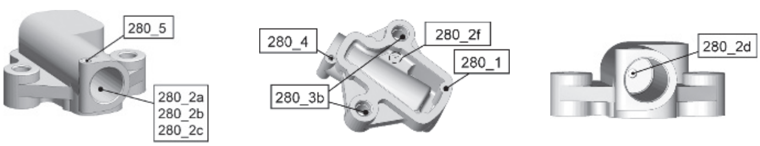
(a) (b)

Fig. 10.5 Working directions (**a**) Product code 280 (**b**) Product code 380



(a) (b)

Fig. 10.6 Working directions (**a**) Product code 500 (**b**) Product code 900



(a) (b) (c)

Fig. 10.7 Representation of the machining features of product code 280

Table 10.2 Machining features of product code 240

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
240_1A	planar_face	26.8	−7.1	−22.1	0.000	0.000	−1.000	D1
240_1B	planar_face	−26.8	−3.8	−22.1	0.000	0.000	−1.000	D1
240_2a	round_hole	5.9	−1.2	12.2	0.000	0.000	1.000	D2
240_2b	round_hole	5.9	−1.2	12.2	0.000	0.000	1.000	D2
240_2c	round_hole	5.9	−1.2	12.2	0.000	0.000	1.000	D2
240_2d	round_hole	5.9	−1.2	−15.8	0.000	0.000	1.000	D2
240_5a	round_hole	−16.7	−1.2	−9.3	−0.842	0.000	0.539	D3
240_5b	round_hole	−16.7	−1.2	−9.3	−0.842	0.000	0.539	D3
240_6	round_hole	−15.7	−1.2	−20.9	−0.537	0.000	−0.843	D4
240_7	round_hole	8.0	−12.6	18.1	−0.612	0.791	0.000	D5
240_8A	round_hole	26.8	−7.1	−22.1	0.000	0.000	−1.000	D1
240_8B	round_hole	−26.8	−3.8	−22.1	0.000	0.000	−1.000	D1

x = placement_location_x; y = placement_location_y; z = placement_location_z; (cos_x, cos_y, cos_z) = direction cosines of the working direction

Table 10.3 Machining features of product code 260

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
260_1	planar_face	16.4	0.0	−24.8	0.000	0.000	−1.000	D1
260_10b	round_hole	−0.6	0.0	17.8	0.000	0.000	−1.000	D1
260_10c	round_hole	−0.6	0.0	17.8	0.000	0.000	−1.000	D1
260_11	compound_feature	−11.9	−8.8	−18.3	−1.000	0.000	0.000	D2
260_2a	round_hole	−0.6	0.0	−12.8	0.000	0.000	−1.000	D1
260_2b	round_hole	−0.6	0.0	−12.8	0.000	0.000	−1.000	D1
260_2c	round_hole	−0.6	0.0	17.8	0.000	0.000	−1.000	D1
260_2d	round_hole	−0.6	0.0	22.6	0.000	0.000	−1.000	D1
260_2e	round_hole	−0.6	0.0	−12.8	0.000	0.000	−1.000	D1
260_7a	round_hole	16.9	14.2	20.8	0.777	0.630	0.000	D3
260_7b	round_hole	16.9	14.2	20.8	0.777	0.630	0.000	D3

x = placement_location_x; y = placement_location_y; z = placement_location_z; (cos_x, cos_y, cos_z) = direction cosines of the working direction

Table 10.4 Machining features of product code 270

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
270_1	planar_face	0.0	0.0	−13.0	0.000	0.000	−1.000	D1
270_15	round_hole	−28.0	−9.0	−7.0	0.000	0.000	−1.000	D1
270_2c	round_hole	24.5	−9.0	3.0	1.000	0.000	0.000	D2
270_2d	round_hole	−23.5	−9.0	3.0	1.000	0.000	0.000	D2
270_3b	replicate_feature (round_hole)	7.6	14.6	−13.0	0.000	0.000	−1.000	D1
270_4	round_hole	21.5	−16.0	−7.0	0.000	0.000	−1.000	D1
270_a	round_hole	24.5	−9.0	3.0	1.000	0.000	0.000	D2

Table 10.4 (continued)

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
270_b	round_hole	24.5	−9.0	3.0	1.000	0.000	0.000	D2
270_e	planar_face	24.5	−9.0	3.0	1.000	0.000	0.000	D2

x = placement_location_x; y = placement_location_y; z = placement_location_z; (cos_x, cos_y, cos_z) = direction cosines of the working direction

Table 10.5 Machining features of product code 280

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
280_1	planar_face	0.0	−2.0	−11.4	0.000	0.000	−1.000	D1
280_2a	round_hole	−0.4	31.0	1.4	0.000	1.000	0.000	D2
280_2b	round_hole	−0.4	31.0	1.4	0.000	1.000	0.000	D2
280_2c	round_hole	−0.4	31.0	1.4	0.000	1.000	0.000	D2
280_2d	round_hole	−0.4	−17.4	1.4	0.000	1.000	0.000	D2
280_2f	round_hole	−12.2	1.6	−5.4	0.000	0.000	−1.000	D1
280_3b	replicate_feature (round_hole)	21.7	−1.6	−11.4	0.000	0.000	−1.000	D1
280_4	compound_feature	6.6	27.5	−8.6	0.000	0.000	−1.000	D1
280_5	compound_feature	6.6	27.5	11.4	0.000	0.000	1.000	D3

x = placement_location_x; y = placement_location_y; z = placement_location_z; (cos_x, cos_y, cos_z) = direction cosines of the working direction

Table 10.6 Machining features of product code 380

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
380_1	replicate_feature (planar_face)	−6.8	17.2	−20.6	0.000	1.000	0.000	D1
380_11	planar_face	−5.8	−41.6	33.9	0.000	−1.000	0.000	D2
380_12a	replicate_feature (round_hole)	4.1	24.2	8.9	0.000	1.000	0.000	D1
380_12b	compound_feature	4.1	24.2	8.9	0.000	1.000	0.000	D1
380_13	planar_face	12.5	33.7	−43.7	0.000	1.000	0.000	D1
380_14a	round_hole	10.9	−9.5	29.6	0.000	1.000	0.000	D1
380_14b	compound_feature	10.9	−9.5	29.6	0.000	1.000	0.000	D1
380_16a	compound_feature	18.2	−41.6	33.9	0.000	−1.000	0.000	D2
380_16b	compound_feature	−29.8	−41.6	33.9	0.000	−1.000	0.000	D2
380_16c	replicate_feature (round_hole)	−5.8	−41.6	33.9	0.000	−1.000	0.000	D2
380_17	planar_face	24.6	48.9	−57.1	0.000	0.000	−1.000	D3
380_18	replicate_feature (round_hole)	35.1	12.4	−57.1	0.000	0.000	−1.000	D3
380_19a	replicate_feature (round_hole)	−18.8	−3.3	−57.1	0.000	0.000	−1.000	D3

Table 10.6 (continued)

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
380_2	compound_feature	−6.8	17.2	−20.6	0.000	1.000	0.000	D1
380_20a	replicate_feature (planar_face)	35.2	−3.3	−36.6	1.000	0.000	0.000	D4
380_20c	replicate_feature (round_hole)	35.2	−3.3	−36.6	1.000	0.000	0.000	D4
380_21	planar_face	28.2	−29.3	−20.6	1.000	0.000	0.000	D4
380_22a	replicate_feature (round_hole)	28.2	−29.3	−20.6	1.000	0.000	0.000	D4
380_22b	replicate_feature (round_hole)	28.2	−29.3	−20.6	1.000	0.000	0.000	D4
380_3	replicate_feature (round_hole)	12.5	33.7	−43.7	0.000	1.000	0.000	D1
380_4	planar_face	−12.2	−33.7	−20.6	−0.906	−0.423	0.000	D5
380_5	compound_feature	−12.2	−33.7	−20.6	−0.906	−0.423	0.000	D5
380_6a	replicate_feature (thread)	−12.2	−33.7	−20.6	−0.906	−0.423	0.000	D5
380_6b	replicate_feature (thread)	−12.2	−33.7	−20.6	−0.906	−0.423	0.000	D5

x = placement_location_x; y = placement_location_y; z = placement_location_z; (cos_x, cos_y, cos_z) = direction cosines of the working direction

Table 10.7 Machining features of product code 500

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
500_1	planar_face	−48.0	−0.2	−16.9	−1.000	0.000	0.000	D1
500_10a	compound_feature	−42.5	−35.8	−40.0	0.000	−1.000	0.000	D2
500_10b	round_hole	−42.5	−35.8	−40.0	0.000	−1.000	0.000	D2
500_11	planar_face	−64.5	24.2	−34.4	−1.000	0.000	0.000	D1
500_12a	compound_feature	−55.0	2.8	14.5	−1.000	0.000	0.000	D1
500_12b	compound_feature	−55.0	2.8	14.5	−1.000	0.000	0.000	D1
500_16a	compound_feature	−64.5	−20.2	51.0	−1.000	0.000	0.000	D1
500_16ac	compound_feature	−64.5	16.0	−30.2	−1.000	0.000	0.000	D1
500_16b	round_hole	−64.5	−20.2	51.0	−1.000	0.000	0.000	D1
500_2	compound_feature	−48.0	−0.2	−16.9	−1.000	0.000	0.000	D1
500_3	replicate_feature (round_hole)	−64.5	24.2	−34.4	−1.000	0.000	0.000	D1
500_4	planar_face	43.1	8.8	−16.9	0.420	0.910	0.000	D4
500_5	compound_feature	43.1	8.8	−16.9	0.420	0.910	0.000	D4
500_6a	replicate_feature (round_hole)	43.1	8.8	−16.9	0.420	0.910	0.000	D4
500_6b	replicate_feature (round_hole)	43.1	8.8	−16.9	0.420	0.910	0.000	D4
500_7	planar_face	−12.5	−37.8	−16.9	0.000	1.000	0.000	D3

Table 10.7 (continued)

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
500_8a	replicate_feature (thread)	−23.8	37.8	18.5	0.000	1.000	0.000	D3
500_8b	replicate_feature (thread)	−23.8	37.8	18.5	0.000	1.000	0.000	D3
500_9	planar_face	−12.5	−35.8	−16.9	0.000	−1.000	0.000	D2

x = placement_location_x; y = placement_location_y; z = placement_location_z; (cos_x, cos_y, cos_z) = direction cosines of the working direction

Table 10.8 Machining features of product code 900

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
900_10	replicate_feature (round_hole)	−16.0	−43.9	−76.8	0.000	−1.000	0.000	D1
900_12a	compound_feature	−16.0	−12.4	60.6	0.000	0.000	1.000	D2
900_12b	compound_feature	−16.0	−12.4	60.6	0.000	0.000	1.000	D2
900_15	replicate_feature (round_hole)	33.3	−31.8	79.7	0.000	0.000	1.000	D2
900_15A	replicate_feature (round_hole)	17.0	40.2	79.7	0.000	0.000	1.000	D2
900_21a	round_hole	14.8	−2.5	61.5	0.000	0.000	1.000	D2
900_21b	compound_feature	14.8	−2.5	61.5	0.000	0.000	1.000	D2
900_22a	replicate_feature (planar_face)	40.0	−6.2	75.5	0.000	0.000	1.000	D2
900_22b	replicate_feature (round_hole)	40.0	−6.2	75.5	0.000	0.000	1.000	D2
900_2a	compound_feature	40.0	−6.2	14.9	0.000	0.000	1.000	D2
900_2b	replicate_feature (planar_face)	33.3	−31.8	79.7	0.000	0.000	1.000	D2
900_4	planar_face	−16.0	−5.5	−50.9	0.000	1.000	0.000	D3
900_5	compound_feature	−16.0	−5.5	−50.9	0.000	0.907	−0.422	D4
900_6a	replicate_feature (thread)	−16.0	−5.5	−50.9	0.000	0.907	−0.422	D4
900_6b	replicate_feature (thread)	−16.0	−5.5	−50.9	0.000	0.907	−0.422	D4
900_7	planar_face	−16.0	30.1	11.1	0.000	1.000	0.000	D3
900_8a	replicate_feature (thread)	−57.6	30.1	−2.6	0.000	1.000	0.000	D3
900_8b	replicate_feature (thread)	−57.6	30.1	−2.6	0.000	1.000	0.000	D3
900_9	planar_face	−16.0	−43.9	−76.8	0.000	−1.000	0.000	D1

x = placement_location_x; y = placement_location_y; z = placement_location_z; (cos_x, cos_y, cos_z) = direction cosines of the working direction

Table 10.9 Machining operations

id_oper	its_tool	type	id_oper	its_tool	type	id_oper	its_tool	type
o0	0	Rolling	o56	56	Milling	o141	141	Drilling
o1	1	Milling	o57	57	Milling	o142	142	Milling
o2	2	Milling	o60	60	Drilling	o181	181	Milling
o3	3	Drilling	o61	61	Drilling	o182	182	Drilling
o4	4	Drilling	o63	63	Drilling	o183	183	Milling
o5	5	Drilling	o65	65	Milling	o211	211	Drilling
o6	6	Milling	o67	67	Drilling	o221	221	Drilling
o7	7	Milling	o78	78	Milling	o222	222	Milling
o8	8	Milling	o80	80	Drilling	o231	231	Drilling
o9	9	Drilling	o81	81	Drilling	o241	241	Drilling
o15	15	Drilling	o85	85	Milling	o251	251	Drilling
o16	16	Drilling	o97	97	Drilling	o252	252	Milling
o17	17	Threading	o101	101	Drilling	o261	261	Drilling
o19	19	Centering	o102	102	Drilling	o262	262	Drilling
o20	20	Drilling	o111	111	Drilling	o311	311	Boring
o27	27	Boring	o112	112	Threading	o322	322	Drilling
o28	28	Drilling	o121	121	Drilling	o333	333	Drilling
o50	50	Milling	o123	123	Drilling	o344	344	Drilling
o52	52	Drilling	o131	131	Drilling	o355	355	Drilling
o53	53	Milling	o132	132	Milling	o651	651	Drilling
o55	55	Milling						

id_oper = id_operation; type = operation_type

Using data concerning machining features and machining operations, the whole set of machining workingsteps has been defined, in accordance to the data formalization of Chap. 4 (see Sect. 4.3.3 and Table 4.16). In Tables 10.10 and 10.11 all the machining workingsteps are reported together with their cutting time.

Table 10.10 Machining workingsteps of product codes 240, 260, 270 and 280

mws	its_feature	oper	time [s]	mws	its_feature	oper	time [s]
ws01	240_1A	o8	3.05	ws22	260_2d	o241	5
ws02	240_1B	o8	3.05	ws23	260_10c	o231	4.22
ws03	240_5a	o9	6.1	ws24	270_1	o181	5.5
ws04	240_2d	o101	3.81	ws25	270_4	o251	5.29
ws05	240_2a	o111	4.49	ws26	270_a	o261	5.49
ws06	240_2b	o121	5.42	ws27	270_b	o121	5.47
ws07	240_6	o131	5.06	ws28	270_e	o85	2.34
ws08	240_7	o141	3.69	ws29	270_3b	o27	5.46
ws09	240_8A	o27	2.95	ws30	270_2d	o28	4.02
ws10	240_8B	o27	2.95	ws31	270_15	o81	4.8
ws11	240_5b	o16	6.07	ws32	270_2c	o0	4.75
ws12	240_2c	o0	5.04	ws95	280_1	o183	6.1

Table 10.10 (continued)

mws	its_feature	oper	time [s]	mws	its_feature	oper	time [s]
ws13	260_1	o181	4.95	ws96	280_4	o344	5.3
ws14	260_7a	o19	3.51	ws97	280_5	o355	4.3
ws15	260_10b	o20	2.81	ws98	280_2a	o261	5.5
ws16	260_2c	o20	2.19	ws99	280_2b	o123	5.8
ws17	260_2a	o211	4.97	ws100	280_3b	o311	6
ws18	260_2b	o121	4.95	ws101	280_2d	o322	4.1
ws19	260_2e	o0	3.85	ws102	280_2c	o0	5.35
ws20	260_7b	o221	4.96	ws103	280_2f	o333	4.4
ws21	260_11	o97	4.01				

mws = id_workingstep; oper = its_operation; time = ws_cutting_time

Table 10.11 Machining workingsteps of product codes 380, 500 and 900

mws	its_feature	oper	time [s]	mws	its_feature	oper	time [s]
ws52	380_21	o50	6.37	ws40	500_7	o78	8.94
ws53	380_20a	o50	6.37	ws41	500_8a	o17	4.18
ws54	380_4	o50	8.17	ws42	500_8b	o17	8.35
ws55	380_11	o53	13.2	ws43	500_6a	o111	4.65
ws56	380_16a	o52	4.59	ws44	500_6b	o111	8.18
ws57	380_16b	o52	3.17	ws45	500_5	o221	5.15
ws58	380_13	o53	4.67	ws46	500_3	o211	8.55
ws59	380_14a	o262	5.97	ws47	500_12a	o231	8.63
ws60	380_14b	o55	5.78	ws48	500_12b	o241	4.83
ws61	380_16c	o56	4.48	ws49	500_16b	o56	4.53
ws62	380_17	o57	8.55	ws50	500_10a	o67	10.5
ws63	380_1	o78	16.4	ws51	500_10b	o67	7.41
ws64	380_2	o252	4.57	ws76	900_9	o1	17.9
ws65	380_3	o63	7.88	ws77	900_22a	o2	3.77
ws66	380_22a	o102	8.88	ws78	900_22b	o3	8.34
ws67	380_22b	o102	7.42	ws79	900_15	o4	4.59
ws68	380_20c	o60	16.8	ws80	900_21a	o5	5.48
ws69	380_12a	o61	3.63	ws81	900_21b	o6	5.33
ws70	380_19a	o60	7.97	ws82	900_15A	o4	6.82
ws71	380_18	o651	7.85	ws83	900_2a	o7	9
ws72	380_5	o222	9.67	ws84	900_12a	o80	9.27
ws73	380_6a	o17	5.28	ws85	900_4	o1	7.17
ws74	380_6b	o17	5.82	ws86	900_7	o1	10.7
ws75	380_12b	o182	8.83	ws87	900_8a	o102	5
ws33	500_9	o65	17.6	ws88	900_8b	o102	11.7
ws34	500_11	o53	10.3	ws89	900_6a	o112	4.65
ws35	500_16a	o52	4.47	ws90	900_6b	o112	8.18
ws36	500_16ac	o52	3.15	ws91	900_5	o222	5.15
ws37	500_1	o78	13.4	ws92	900_2b	o132	12.3
ws38	500_2	o251	4.57	ws93	900_12b	o142	4.79
ws39	500_4	o78	9.02	ws94	900_10	o15	15.4

mws = id_workingstep; oper = its_operation; time = ws_cutting_time

Moreover, technological constraints among machining workingsteps must be considered. These constraints can be precedence constraints (i.e. a machining workingstep must be executed after another one) or tolerance constraints (i.e. two machining workingsteps must be processed on the same machine and same setup in order to guarantee the required precision level). Precedence constraints are reported in Table 10.12, while tolerance constraints are given in Table 10.13.

Table 10.12 Precedence constraints among machining workingsteps

pred	succ	pred	succ	pred	succ	pred	succ
ws01	ws07	ws27	ws30	ws52	ws66	ws73	ws74
ws01	ws09	ws30	ws32	ws53	ws68	ws76	ws94
ws02	ws10	ws33	ws50	ws54	ws72	ws77	ws78
ws03	ws11	ws34	ws35	ws54	ws73	ws79	ws82
ws04	ws05	ws34	ws36	ws55	ws56	ws80	ws81
ws05	ws06	ws35	ws49	ws55	ws57	ws83	ws92
ws06	ws12	ws36	ws49	ws56	ws61	ws84	ws93
ws101	ws102	ws37	ws38	ws57	ws61	ws85	ws89
ws14	ws20	ws37	ws46	ws58	ws59	ws85	ws91
ws15	ws23	ws39	ws43	ws59	ws60	ws86	ws87
ws16	ws17	ws39	ws45	ws62	ws70	ws87	ws88
ws17	ws18	ws40	ws41	ws62	ws71	ws89	ws90
ws18	ws19	ws41	ws42	ws63	ws64	ws95	ws100
ws19	ws22	ws43	ws44	ws63	ws65	ws98	ws99
ws24	ws29	ws47	ws48	ws66	ws67	ws99	ws101
ws26	ws27	ws50	ws51	ws69	ws75		

pred = predecessor; succ = successor

Table 10.13 Tolerance constraints among machining workingsteps

mws1	mws2	mws1	mws2	mws1	mws2
ws01	ws02	ws26	ws27	ws53	ws62
ws03	ws11	ws27	ws30	ws56	ws57
ws06	ws12	ws30	ws32	ws58	ws59
ws09	ws10	ws35	ws36	ws59	ws60
ws14	ws20	ws37	ws38	ws63	ws64
ws15	ws16	ws41	ws42	ws69	ws75
ws16	ws17	ws43	ws44	ws96	ws97
ws17	ws18	ws46	ws47	ws97	ws100
ws18	ws19	ws49	ws50	ws98	ws99
ws22	ws23	ws50	ws51	ws99	ws102

mws1 = first machining workingstep of the couple of wokingsteps that must be executed on the same pallet and on the same machine; mws2 = second machining workingstep of the couple of wokingsteps that must be executed on the same pallet and on the same machine

10.2.2 Railway Components

The family of products for railway applications consist of two products: “cannotto” (product code 101) and “catenaccio” (product code 102). For each workpiece type a 3D drawing is reported in Figs. 10.8 and 10.9.

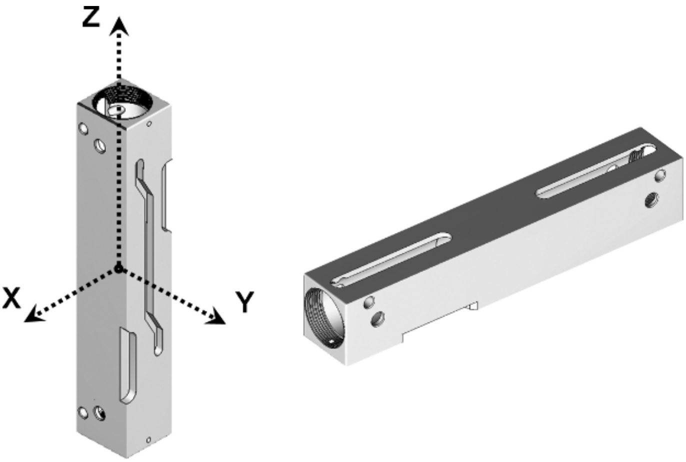


Fig. 10.8 Product code 101

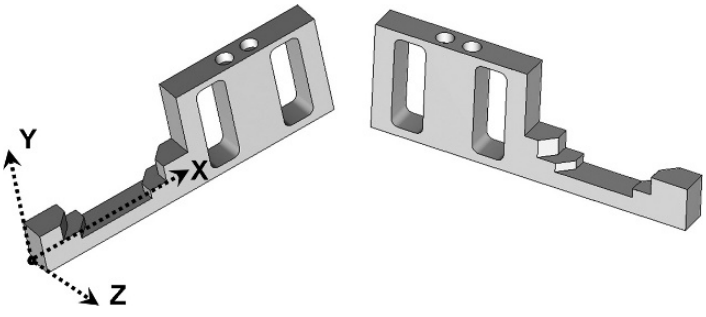


Fig. 10.9 Product code 102

Table 10.14 provides the information on the material and the dimensions related to the bounding geometry.

As for the first family, each workpiece type has been technologically analyzed and the information has been formalized according to the framework provided in Chap. 4. Starting from the list of machining feature, described by direction cosines, it is possible to determine the corresponding working directions. In particular, the data concerning the machining features are listed in Tables 10.15 and 10.16. Figures 10.10 and 10.11 illustrate the working directions.

Table 10.14 Characteristics and dimensions of the workpiece types

id_workpiece	its_material	x_pos [mm]	x_neg [mm]	y_pos [mm]	y_neg [mm]	z_pos [mm]	z_neg [mm]
101	41CrMo4-UNI8551	35	–35	38	–38	215	–215
102	41CrMo4-UNI8551	15	–15	350	0	120	0

x_pos = x_bounding_pos; x_neg = x_bounding_neg; y_pos = y_bounding_pos; y_neg = y_bounding_neg; z_pos = z_bounding_pos; z_neg = z_bounding_neg

Table 10.15 Machining features of product code 101

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
101BH01	button_hole	0	–38	130	0	–1	0	D5
101BH02	button_hole	0	–38	–130	0	–1	0	D5
101Ch01	round_hole	–35	–28	–185	–1	0	0	D4
101Ch02	round_hole	–35	–28	185	–1	0	0	D4
101Ch03	round_hole	–35	–3	–174	–1	0	0	D4
101Ch04	round_hole	–35	–3	174	–1	0	0	D4
101Ch05	round_hole	35	–28	–185	1	0	0	D1
101Ch06	round_hole	35	–28	185	1	0	0	D1
101Ch07	round_hole	35	–3	–174	1	0	0	D1
101Ch08	round_hole	35	–3	174	1	0	0	D1
101Ch09	planar_face	27.5	38	–98	1	0	0	D1
101Ch11	button_hole	0	–38	130	0	–1	0	D5
101Ch12	planar_face	0	38	31.75	1	0	0	D1
101Ho01	round_hole	–35	–28	–185	–1	0	0	D4
101Ho02	round_hole	–35	–28	185	–1	0	0	D4
101Ho03	round_hole	–35	–3	–174	–1	0	0	D4
101Ho04	round_hole	–35	–3	174	–1	0	0	D4
101Ho05	round_hole	35	–28	–185	1	0	0	D1
101Ho06	round_hole	35	–28	185	1	0	0	D1
101Ho07	round_hole	35	–3	–174	1	0	0	D1
101Ho08	round_hole	35	–3	174	1	0	0	D1
101Ho09	round_hole	0	0	–215	0	0	–1	D6
101Ho10	round_hole	0	0	215	0	0	1	D3
101Ho11	round_hole	0	38	–206	0	1	0	D2
101Ho12	round_hole	0	38	206	0	1	0	D2
101PF01	planar_face	0	38	0	0	1	0	D2
101PF02	planar_face	–35	0	0	–1	0	0	D4
101PF03	planar_face	0	–38	0	0	–1	0	D5
101PF04	planar_face	35	0	0	1	0	0	D1
101PF05	planar_face	0	0	–215	0	0	–1	D6
101PF06	planar_face	0	0	215	0	0	1	D3
101PF07	planar_face	27.5	38	–98	1	0	0	D1
101PF08	planar_face	–27.5	38	98	1	0	0	D1
101PF09	planar_face	0	38	31.75	1	0	0	D1

x = placement_location_x; y = placement_location_y; z = placement_location_z; (cos_x, cos_y, cos_z) = direction cosines of the working direction

Table 10.16 Machining features of product code 102

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
102Ho1	Hole	15	129.5	60	1	0	0	D1
102Ho10	Hole	15	49	18	1	0	0	D1
102Ho11	Hole	15	120	104	1	0	0	D1
102Ho12	Hole	15	139	104	1	0	0	D1
102Ho13	Hole	15	120	18	1	0	0	D1
102Ho14	Hole	15	139	18	1	0	0	D1
102Ho2	Hole	15	39.5	60	1	0	0	D1
102Ho3	Hole	–15	129.5	60	–1	0	0	D4
102Ho4	Hole	–15	39.5	60	–1	0	0	D4
102Ho5	round_hole	0	69.5	120	0	0	1	D3
102Ho6	round_hole	0	99.5	120	0	0	1	D3
102Ho7	Hole	15	30	104	1	0	0	D1
102Ho8	Hole	15	49	104	1	0	0	D1
102Ho9	Hole	15	30	18	1	0	0	D1
102PF01	planar_face	0	84.5	120	0	0	1	D3
102PF02	planar_face	–15	175	60	–1	0	0	D4
102PF03	planar_face	0	350	24	0	1	0	D2
102PF04	planar_face	0	0	60	0	–1	0	D5
102PF05	planar_face	0	199	48	0	0	1	D3
102PF06	planar_face	0	330	48	0	0	1	D3
102PF0506	planar_face	0	264	48	0	0	1	D3
102PF07	planar_face	0	300	28	0	0	1	D3
102PF08	planar_face	0	209	28	0	0	1	D3
102PF09	planar_face	0	249.5	18	0	0	1	D3
102PF10	planar_face	0	169	84	0	1	0	D2
102PF11	planar_face	15	175	60	1	0	0	D1
102PF12	planar_face	0	175	0	0	0	–1	D6

x = placement_location_x; y = placement_location_y; z = placement_location_z; (cos_x, cos_y, cos_z) = direction cosines of the working direction

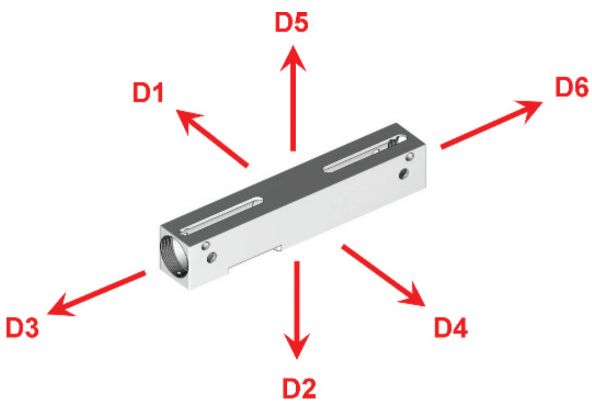


Fig. 10.10 Working directions of product code 101

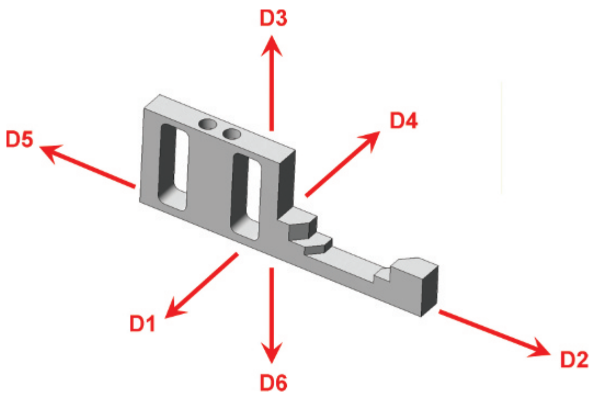


Fig. 10.11 Working directions product code 102

Once the machining features have been determined, the machining operations can be defined (Tables 10.17 and 10.18). As defined in Chap. 4, each operation can be characterised by its type and the required tool. Tools are synthetically indicated discarding technical details and paying attention to the operation type.

The machining workingsteps are listed in Tables 10.19 and 10.20.

Table 10.17 Machining operations of product code 101

id_oper	its_tool	type	id_oper	its_tool	type
101Mi01	T01	Milling	101Mi10	T12	Milling
101Mi02	T02	Milling	101Th03	T29	Threading
101Mi03	T02	Milling	101Mi11	T13	Milling
101Mi04	T03	Milling	101Ch05	T14	Chamfering
101Mi05	T03	Milling	101Bo03	T15	Boring
101Mi06	T03	Milling	101Dr07	T16	Drilling
101Dr01	T04	Drilling	101Dr12	T28	Drilling
101Dr02	T05	Drilling	101Ch06	T17	Chamfering
101Ch01	T05	Chamfering	101Dr09	T18	Drilling
101Ch02	T06	Chamfering	101Gr01	T19	Groove
101Bo01	T07	Boring	101Th01	T20	Threading
101Dr03	T04	Drilling	101Bo05	T21	Boring
101Bo02	T07	Boring	101Dr11	T22	Drilling
101Mi07	T03	Milling	101Mi11	T13	Milling
101Ce01	T09	Centering	101Ch11	T24	Chamfering
101Dr04	T09	Drilling	101Ch12	T25	Chamfering
101Mi09	T03	Milling	101Mi12	T23	Milling
101Dr06	T05	Drilling	101Mi13	T27	Milling
101Ch03	T10	Chamfering	101Ce03	T28	Centering
101Ch04	T11	Chamfering			

id_oper = id_operation; type = operation_type

Table 10.18 Machining operations of product code 102

id_oper	its_tool	type	id_oper	its_tool	type
102Mi01	TT01	Milling	102Mi12	TT10	Milling
102Mi02	TT02	Milling	102Mi13	TT11	Milling
102Mi03	TT02	Milling	102Mi14	TT12	Milling
102Dr01	TT03	Drilling	102Dr02	TT13	Drilling
102Mi04	TT04	Milling	102Mi15	TT14	Milling
102Mi06	TT06	Milling	102Mi16	TT15	Milling
102Mi07	TT06	Milling	102Mi17	TT16	Milling
102Mi08	TT07	Milling	102Mi18	TT02	Milling
102Mi09	TT07	Milling	102Mi19	TT06	Milling
102Mi10	TT08	Milling	102Dr03	TT17	Drilling
102Mi11	TT09	Milling	102Mi21	TT18	Milling

id_oper = id_operation; type = operation_type

Table 10.19 Machining workingsteps of product code 101

mws	its_feature	oper	time [s]	mws	its_feature	oper	time [s]
1BnH01D11	101BH01	101Dr11	19	1H09D07	101Ho09	101Dr07	297
1BnH01M11	101BH01	101Mi11	19	1H09D09	101Ho09	101Dr09	186
1BnH02D11	101BH02	101Dr11	19	1H09GR01	101Ho09	101Gr01	396
1BnH02M11	101BH02	101Mi11	19	1H09TH01	101Ho09	101Th01	135
1Chmf01CH01	101Ch01	101Ch01	36	1H10B03	101Ho10	101Bo03	213
1Chmf02CH01	101Ch02	101Ch01	36	1H10B05	101Ho10	101Bo05	135
1Chmf03CH02	101Ch03	101Ch02	36	1H10C01	101Ho10	101Ce01	54
1Chmf04CH02	101Ch04	101Ch02	36	1H10CH06	101Ho10	101Ch06	135
1Chmf05CH04	101Ch05	101Ch04	54	1H10D04	101Ho10	101Dr04	45
1Chmf06CH04	101Ch06	101Ch04	54	1H10D07	101Ho10	101Dr07	297
1Chmf07CH03	101Ch07	101Ch03	54	1H10D09	101Ho10	101Dr09	186
1Chmf07CH11	101Ch07	101Ch11	24	1H10TH01	101Ho10	101Th01	135
1Chmf08CH03	101Ch08	101Ch03	54	1H11C03	101Ho11	101Ce03	36
1Chmf08CH11	101Ch08	101Ch11	24	1H11D12	101Ho11	101Dr12	39
1Chmf09CH05	101Ch09	101Ch05	72	1H11TH03	101Ho11	101Th03	72
1Chmf09CH12	101Ch09	101Ch12	24	1H12C03	101Ho12	101Ce03	36
1H01B01	101Ho01	101Bo01	63	1H12D12	101Ho12	101Dr12	39
1H01D01	101Ho01	101Dr01	63	1H12TH03	101Ho12	101Th03	498
1H02B01	101Ho02	101Bo01	63	1Pf01M01	101PF01	101Mi01	498
1H02D01	101Ho02	101Dr01	63	1Pf01M09	101PF01	101Mi09	366
1H03D02	101Ho03	101Dr02	63	1Pf02M02	101PF02	101Mi02	420
1H04D02	101Ho04	101Dr02	63	1Pf03M03	101PF03	101Mi03	498
1H05B02	101Ho05	101Bo02	23	1Pf04M04	101PF04	101Mi04	120
1H05D03	101Ho05	101Dr03	27	1Pf05M05	101PF05	101Mi05	138
1H06B02	101Ho06	101Bo02	23	1Pf05M07	101PF05	101Mi07	99
1H06D03	101Ho06	101Dr03	27	1Pf06M06	101PF06	101Mi06	204
1H07D06	101Ho07	101Dr06	117	1Pf06M07	101PF06	101Mi07	99
1H08D06	101Ho08	101Dr06	117	1Pf07M10	101PF07	101Mi10	90

Table 10.19 (continued)

mws	its_feature	oper	time [s]	mws	its_feature	oper	time [s]
1H09B03	101Ho09	101Bo03	213	1Pf07M13	101PF07	101Mi13	66
1H09B05	101Ho09	101Bo05	135	1Pf08M10	101PF08	101Mi10	90
1H09C01	101Ho09	101Ce01	54	1Pf08M13	101PF08	101Mi13	66
1H09CH06	101Ho09	101Ch06	135	1Pf09M11	101PF09	101Mi11	66
1H09D04	101Ho09	101Dr04	45	1Pf09M12	101PF09	101Mi12	144

mws = id_workingstep; feat = its_feature; oper = its_operation; time = ws_cutting_time

Table 10.20 Machining workingsteps of product code 102

mws	its_feature	oper	time [s]	mws	its_feature	oper	time [s]
2H10D03	102Ho10	102Dr03	26	2Pf01M12	102PF01	102Mi12	51
2H11D03	102Ho11	102Dr03	26	2Pf02M02	102PF02	102Mi02	132
2H12D03	102Ho12	102Dr03	26	2Pf02M06	102PF02	102Mi06	210
2H1D01	102Ho1	102Dr01	108	2Pf03M03	102PF03	102Mi03	111
2H2D01	102Ho2	102Dr01	108	2Pf03M07	102PF03	102Mi07	96
2H3M04	102Ho3	102Mi04	102	2Pf04M03	102PF04	102Mi03	111
2H3M21	102Ho3	102Mi21	108	2Pf04M07	102PF04	102Mi07	96
2H4M04	102Ho4	102Mi04	102	2Pf05M11	102PF05	102Mi11	22.4
2H4M21	102Ho4	102Mi21	108	2Pf05M14	102PF05	102Mi14	27
2H5D02	102Ho5	102Dr02	44	2Pf06M11	102PF06	102Mi11	22.4
2H5D03	102Ho5	102Dr03	26	2Pf06M14	102PF06	102Mi14	27
2H5M15	102Ho5	102Mi15	39	2Pf07M11	102PF07	102Mi11	22.4
2H5M16	102Ho5	102Mi16	33	2Pf07M14	102PF07	102Mi14	27
2H5M17	102Ho5	102Mi17	36	2Pf08M11	102PF08	102Mi11	22.4
2H6D02	102Ho6	102Dr02	44	2Pf08M14	102PF08	102Mi14	27
2H6D03	102Ho6	102Dr03	26	2Pf09M11	102PF09	102Mi11	22.4
2H6M15	102Ho6	102Mi15	39	2Pf09M13	102PF09	102Mi13	69
2H6M16	102Ho6	102Mi16	33	2Pf10M10	102PF10	102Mi10	108
2H6M17	102Ho6	102Mi17	36	2Pf10M13	102PF10	102Mi13	69
2H7D03	102Ho7	102Dr03	26	2Pf11M18	102PF11	102Mi18	138
2H8D03	102Ho8	102Dr03	26	2Pf11M19	102PF11	102Mi19	222
2H9D03	102Ho9	102Dr03	26	2Pf12M08	102PF12	102Mi08	54
2Pf01M01	102PF01	102Mi01	225	2Pf12M12	102PF12	102Mi12	51
2Pf01M08	102PF01	102Mi08	54	2Pf56M09	102PF0506	102Mi09	126

mws = id_workingstep; oper = its_operation; time = ws_cutting_time

For example, referring to product code 102, the machining workingstep 2Pf01M01 includes information on the milling operation 102Mi01 (using tool type TT01) that is performed on the feature 102PF01 (that is the planar face perpendicular to the working direction D1).

Once machining workingsteps have been determined, the technological constraints among machining workingsteps should be analyzed. For instance, the precedence relation between workingsteps 2Pf02M02 (predecessor) and

2H1D01 (successor) stands for the necessity to execute first the milling of planar face 102PF02 and then the drilling of hole 101Ho01 on such a planar face. Tables 10.21 and 10.22 provide the complete list of precedence constraints for product code 101 and 102 respectively.

Table 10.21 Precedence constraints among machining workingsteps of product code 101

Predecessor	Successor	Predecessor	Successor
1Pf04M04	1H01D01	1Pf07M10	1Chmf09CH05
1Pf04M04	1H02D01	1Pf08M10	1Chmf09CH05
1Pf04M04	1H03D01	1H09B03	1H09D07
1Pf04M04	1H04D01	1H09D07	1Chmf05CH05
1H01D01	1Chmf01CH01	1Chmf05CH05	1H09D09
1H02D01	1Chmf02CH01	1H10B03	1H10D07
1H03D01	1Chmf03CH02	1H10D07	1Chmf06CH05
1H04D01	1Chmf04CH02	1Chmf06CH05	1H10D09
1Chmf01CH01	1H01B01	1H09D09	1H09GR01
1Chmf02CH01	1H02B01	1H10D09	1H09GR01
1H06D03	1H06B02	1H09GR01	1H09TH01
1H05D03	1H05B02	1H09GR01	1H10TH01
1Pf05M07	1H09C01	1H09TH01	1H09B05
1H09C01	1H09D04	1H10TH01	1H10B05
1Pf06M07	1H10C01	1BH01D12	1BH01M11
1H10C01	1H10D04	1BH01M11	1Chmf07CH11
1Pf01M09	1H07D06	1BH02D12	1BH02M11
1Pf01M09	1H08D06	1BH02M11	1Chmf08CH11
1Pf01M09	1Chmf05CH04	1Chmf09CH12	1Pf09M12
1Pf01M09	1Chmf06CH04	1H11C03	1H11D12
1Pf01M09	1Pf09M11	1H11D12	1H11TH03
1H07D06	1Chmf07CH03	1H12C03	1H12D12
1H08D06	1Chmf08CH03	1H12D12	1H12TH03

Table 10.22 Precedence constraints among machining workingsteps of product code 102

Predecessor	Successor	Predecessor	Successor	Predecessor	Successor
2Pf02M02	2H1D01	2H5M15	2H5D02	2Pf06M11	2Pf06M14
2Pf02M02	2H2D01	2Pf01M08	2H6M17	2Pf56M09	2Pf07M11
2Pf02M02	2Pf02M06	2H6M17	2H6M16	2Pf07M11	2Pf07M14
2H1D01	2H3M04	2H6M16	2H6M15	2Pf56M09	2Pf08M11
2H2D01	2H4M04	2H6M15	2H6D02	2Pf08M11	2Pf08M14
2Pf03M03	2Pf03M07	2Pf01M08	2Pf01M12	2Pf56M09	2Pf09M11
2Pf04M03	2Pf04M07	2Pf12M08	2Pf12M12	2Pf09M11	2Pf09M13
2Pf01M08	2H5M17	2Pf56M09	2Pf05M11	2Pf56M09	2Pf10M10
2H5M17	2H5M16	2Pf05M11	2Pf05M14	2Pf10M10	2Pf10M13
2H5M16	2H5M15	2Pf56M09	2Pf06M11	2Pf11M18	2Pf11M19

10.2.3 Hydraulic Components

In this section a product belonging to the family of high-pressure valve coupling flanges will be described. The choice of the product type has been driven by the product geometric and technological complexity related to the presence of a radial passing hole, designed for lubrication. Figure 10.12 illustrates a 3D drawing of the product code N016A.

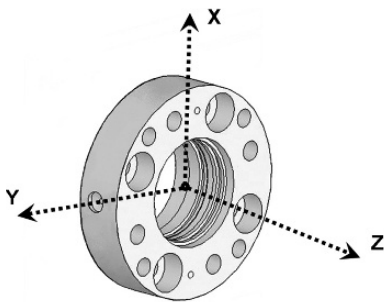


Fig. 10.12 Product code N016A

Information concerning the material and the bounding geometry (i.e. the envelope cube) is listed in Table 10.23. In particular, the material is steel AISI 316 and the origin of the workpiece coordinate system is placed in the center of its envelope cube. The working directions that are necessary to process the workpiece are shown in Fig. 10.13.

Table 10.23 Characteristics and dimensions of the workpiece type

id_workpiece	its_material	x_pos [mm]	x_neg [mm]	y_pos [mm]	y_neg [mm]	z_pos [mm]	z_neg [mm]
N016A	AISI 316	64.00	–64.00	64.00	–64.00	23.75	23.75

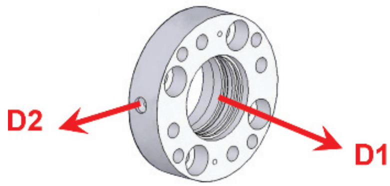


Fig. 10.13 Working directions

Each machining feature has been described in Table 10.24, on the basis of the coordinate system shown in Fig. 10.13 and the definitions of Table 4.2.

Table 10.24 Machining features of product code N016A

id_feature	Abstract supertype	x [mm]	y [mm]	z [mm]	cos_x	cos_y	cos_z	Working direction
016_1_A	round_hole	–38.9	38.9	–20.0	0	0	1	D1
016_1_B	round_hole	–38.9	38.9	–20.0	0	0	1	D1
016_2_A	round_hole	–44.7	19.0	–20.0	0	0	1	D1
016_2_B	round_hole	–44.7	19.0	–20.0	0	0	1	D1
016_3_A	round_hole	–45.3	–19.2	–20.0	0	0	1	D1
016_3_B	round_hole	–45.3	–19.2	–20.0	0	0	1	D1
016_3_C	round_hole	–45.3	–19.2	–7.5	0	0	1	D1
016_4_A	round_hole	–38.9	–38.9	–20.0	0	0	1	D1
016_4_B	round_hole	–38.9	–38.9	–20.0	0	0	1	D1
016_5_A	round_hole	–19.0	–44.7	–20.0	0	0	1	D1
016_5_B	round_hole	–19.0	–44.7	–20.0	0	0	1	D1
016_6_A	round_hole	19.2	–45.3	–20.0	0	0	1	D1
016_6_B	round_hole	19.2	–45.3	–20.0	0	0	1	D1
016_6_C	round_hole	19.2	–45.3	–7.5	0	0	1	D1
016_7_A	round_hole	38.9	–38.9	–20.0	0	0	1	D1
016_7_B	round_hole	38.9	–38.9	–20.0	0	0	1	D1
016_8_A	round_hole	44.7	–19.0	–20.0	0	0	1	D1
016_8_B	round_hole	44.7	–19.0	–20.0	0	0	1	D1
016_9_A	round_hole	45.3	19.2	–20.0	0	0	1	D1
016_9_B	round_hole	45.3	19.2	–20.0	0	0	1	D1
016_9_C	round_hole	45.3	19.2	–7.5	0	0	1	D1
016_10_A	round_hole	38.9	38.9	–20.0	0	0	1	D1
016_10_B	round_hole	38.9	38.9	–20.0	0	0	1	D1
016_11_A	round_hole	19.0	44.7	–20.0	0	0	1	D1
016_11_B	round_hole	19.0	44.7	–20.0	0	0	1	D1
016_12_A	round_hole	–19.2	45.3	–20.0	0	0	1	D1
016_12_B	round_hole	–19.2	45.3	–20.0	0	0	1	D1
016_12_C	round_hole	–19.2	45.3	–7.5	0	0	1	D1
016_13_A	round_hole	0.0	65.0	–4.2	0	1	0	D2
016_13_B	round_hole	0.0	65.0	–4.2	0	1	0	D2
016_13_C	round_hole	0.0	59.2	–4.2	0	1	0	D2

x = placement_location_x; y = placement_location_y; z = placement_location_z; (cos_x, cos_y, cos_z) = direction cosines of the working direction

As shown in Fig. 10.13, some machining operations are characterized by the same working direction. Herein, the concept of replicated feature allows to simplify the product representation. Indeed, a group of identical features can be described by defining the number and the spacing of the features. This is the case of the circle of holes and the mesh of holes (ISO/FDIS 14649-10). In this way, the machining features reported in Table 10.24 can be condensed in the replicate features that are defined in Table 10.25. "Circular_pattern" is a specific type of replicate feature object and describes the pattern assumed by

Table 10.25 Replicate features of product code N016A

Replicate feature	Associated features	Number of features	Base diameter	Angle increment
circular_pattern_1	016_3_A, 016_6_A, 016_9_A, 016_12_A	4	68.59	90°
circular_pattern_2	016_3_B, 016_6_B, 016_9_B, 016_12_B	4	68.59	90°
circular_pattern_3	016_3_C, 016_6_C, 016_9_C, 016_12_C	4	68.59	90°
circular_pattern_4	016_1_A, 016_4_A, 016_7_A, 016_10_A	4	73.33	90°
circular_pattern_5	016_1_B, 016_4_B, 016_7_B, 016_10_B	4	73.33	90°
circular_pattern_6	016_2_A, 016_5_A, 016_8_A, 016_11_A	4	68.59	90°
circular_pattern_7	016_2_B, 016_5_B, 016_8_B, 016_11_B	4	68.59	90°

the group of features ("Associated features"). Table 10.25 lists the main attributes necessary to formalize a circular pattern replicate feature, i.e. the total number of features in the replicate feature, the diameter of the circular pattern and the angle between two elements of the pattern.

The information regarding machining operation and machining workingsteps (see Sect. 4.6 and Table 4.16) is reported in the following tables. In particular, Table 10.26 shows the machining operations, including the tool diameter. Due to the small diameter which characterizes the lubrication hole, the related machining operation (no. 5 in Table 10.26) is performed by a very low feed rate: this facilitates chip removal, avoiding a premature failure of the tool.

Table 10.27 presents the list of machining workingsteps and the related cutting times.

Precedence and tolerance constraints among the machining workingsteps are reported in Tables 10.28 and 10.29 respectively.

Table 10.26 Machining operations of product code N016A

id_oper	type	Spindle speed [rpm]	Feed rate [mm/round]	Tool diameter [mm]
n1	Centering	500	0.1	5
n2	Drilling	1200	0.1	25
n3	Spot-facing	1000	0.1	13
n4	Countersinck cutter	800	0.1	12 (max)
n5	Drilling	400	0.01	4

id_oper = id_operation; type = operation_type

Table 10.27 Machining workingsteps of product code N016A

mws	its_feature	oper	time [s]	mws	its_feature	oper	time [s]
ws01	016_1A	n1	3.6	ws17	016_8A	n1	3.6
ws02	016_1B	n2	16.25	ws18	016_8B	n2	16.25
ws03	016_2A	n1	3.6	ws19	016_9A	n1	3.6
ws04	016_2B	n2	16.25	ws20	016_9B	n2	16.25
ws05	016_3A	n1	3.6	ws21	016_9C	n3	7.5
ws06	016_3B	n3	16.25	ws22	016_10A	n1	3.6
ws07	016_3C	n2	7.5	ws23	016_10B	n2	16.25
ws08	016_4A	n1	3.6	ws24	016_11A	n1	3.6
ws09	016_4B	n2	16.25	ws25	016_11B	n2	16.25
ws10	016_5A	n1	3.6	ws26	016_12A	n1	3.6
ws11	016_5B	n2	16.25	ws27	016_12B	n2	16.25
ws12	016_6A	n1	3.6	ws28	016_12C	n3	7.5
ws13	016_6B	n3	6.25	ws29	016_13A	n1	3.6
ws14	016_6C	n2	7.5	ws30	016_13B	n4	2.25
ws15	016_7A	n1	3.6	ws31	016_13C	n5	390
ws16	016_7B	n2	16.25				

mws = id_workingstep; oper = its_operation; time = ws_cutting_time [s]

Table 10.28 Precedence constraints among machining workingsteps of product code N016A

pred	succ	pred	succ	pred	succ	pred	succ	pred	succ
ws01	ws02	ws08	ws09	ws15	ws16	ws22	ws23	ws29	ws30
ws03	ws04	ws10	ws11	ws15	ws18	ws24	ws25	ws30	ws31
ws05	ws06	ws12	ws13	ws19	ws20	ws26	ws27		
ws06	ws07	ws13	ws14	ws20	ws21	ws27	ws28		

pred = predecessor; succ = successor

Table 10.29 Tolerance constraints among machining workingsteps of product code N016A

mws1	mws2	mws1	mws2	mws1	mws2	mws1	mws2
ws01	ws14	ws06	ws13	ws02	ws06	ws04	ws11
ws21	ws28	ws20	ws27	ws09	ws16	ws18	ws25
ws07	ws28	ws06	ws27	ws16	ws23	ws04	ws25
ws21	ws14	ws20	ws13	ws02	ws16	ws18	ws11
ws07	ws21	ws06	ws20	ws23	ws09	ws25	ws04
ws14	ws28	ws13	ws27	ws01	ws23	ws18	ws11

mws1 = first machining workingstep of the couple of wokingsteps that must be executed on the same pallet and on the same machine; mws2 = second machining workingstep of the couple of wokingsteps that must be executed on the same pallet and on the same machine

10.3 Test Cases

Speaking about FFMS one would like to have an answer to the following questions:

1. Are FFMSs cost effective compared to FMSs?
2. Are FFMS solutions robust? How does the production problem variability impact on the FFMS profitability?
3. Is it worth investing in a stochastic design approach to design an FFMS?

Questions 1 has already been addressed in Chap. 7 where an extensive analysis has been carried out to study which is the impact of the production problem (e.g. the part family, the part mix and the aggregate demand) and of the database of selectable resources (e.g. cost and performance of the machines) on the performance and profitability of Focused Flexibility Manufacturing Systems.

A set of testing experiments have been designed to address the remaining questions and to study:

1. The robustness of FFMS solutions towards changes in the production problem (see Sect. 10.4);
2. The advantage offered by a stochastic approach to design FFMSs (see Sect. 10.5);
3. The reliability of the system performance estimates obtained with the system design model (see Sect. 10.6).

The design of the experiments has been developed starting from the analysis of the results already presented in Chap. 7. Before presenting the experiments and the related results in details, the following sub-sections define the general settings regarding the workpiece types (see Sect. 10.3.1), the selectable machines (see Sect. 10.3.2) and the process planning (see Sect. 10.3.3).

10.3.1 Workpiece Types

The workpiece types used to design the testing experiments have been selected from a set of 24 workpiece types. Some of these correspond to the products that have already been described in Sect. 10.2 (workpiece types 240, 260, 270, 280, 380, 500, 900, 101, 102 and N016A). The other workpiece types have been derived from this original set by applying some modifications (e.g. removal of features), thus creating new product versions (workpiece types 241, 261, 271, 281, 381, 501, 901, 242, 262, 272, 282, 382, 502, 902).

The details regarding the definition of the part mix and the aggregate demand will be presented for each experiment in the following sections.

Among the main characteristics of the workpiece types, much attention is paid to the operation types that are required to machine the products. Indeed, the types of operation strongly influence the possibility of obtaining system solutions that are characterized by the presence of dedicated machines (see Sect. 7.9.2).

10.3.2 Machine Types

As in Chap. 7, three main types of machines have been considered:

- General purpose machines that can execute any kind of machining operation;
- Roughing machines that can perform only roughing operations;
- Drilling machines that can process only drilling operations.

In Chap. 7 it was shown how the cost of dedicated machines influences the profitability of the FFMS solutions, i.e. the difference between the cost of FMS and FFMS solutions.

Therefore in this chapter the experiments have been carried out considering a set of selectable machines consisting of 9 machine types which differ one from another in terms of costs and performance. Of these machines one is a general purpose machine, four are drilling machines and four are roughing machines. The cost reduction of the roughing machines compared to the general purpose machine ranges from 25 to 40%, while the cost reduction of the drilling machines ranges from 15 to 30%. The higher is the cost reduction of the dedicated machines, the worse is their performance. Herein, the machine performance is assumed to impact on the total processing time: a machine with a higher performance can process a part type in a shorter time. All the machines along with their characteristics are reported in Table 10.30. The cost and performance of the dedicated machine are also compared to the general purpose machine, so that it is possible to calculate "Δ Machine Cost %" and "Δ Machine Performance %" (Table 10.30 and Fig. 10.14).

Table 10.30 Selectable machine types

id machine	Precision level	Operation type	Machine cost [c.u.]	Δ Machine cost %	Machine performance	Δ Machine performance %
GP	High	All types	100	0	1	0
R1	Low	All types	60	–40	0.65	–35
R2	Low	All types	65	–35	0.75	–25
R3	Low	All types	70	–30	0.85	–15
R4	Low	All types	75	–25	0.95	–5
D1	High	Only drilling	70	–30	1.05	5
D2	High	Only drilling	75	–25	1.1	10
D3	High	Only drilling	90	–20	1.15	15
D4	High	Only drilling	85	–15	1.2	20

precision level = parameter equal to "low" if only roughing operations can be executed, while it is equal to "high" if both roughing and finishing operations can be executed; operation type = type of operation that can be executed (e.g. drilling, milling, all types, . . .)

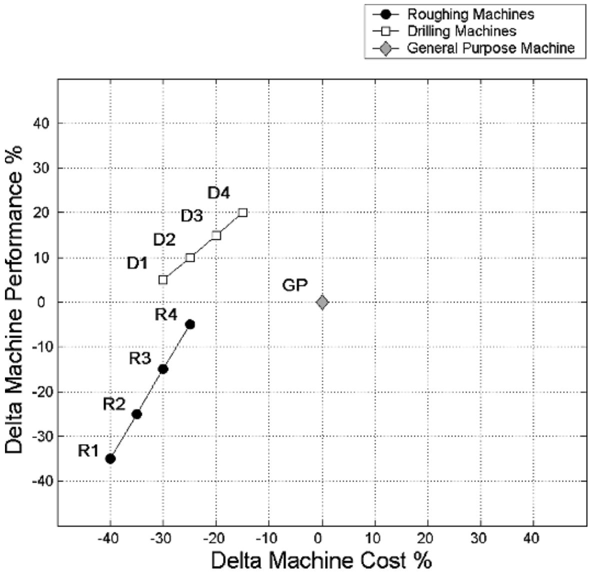


Fig. 10.14 Cost and performance of the dedicated machines compared to the general purpose machine

10.3.3 Process Planning

Process planning is the activity which defines the sequence of operations that are necessary to process the considered workpiece type by means of the selectable resources. The problem has already been addressed in detail within Chap. 6 and the developed methodology has been used to generate the input data required by the application of the FFMS design model presented in Sect. 7.6.

The following tables present the main results of the process planning activity related to workpiece type 240 that has been described in Sect. 10.2 (see Sect. 10.2.1, Tables 10.2, 10.9, 10.10, 10.12 and Figs. 10.1 and 10.4). The first result concerns the setup planning (Table 10.31), i.e. how the workpieces should be positioned on the fixtures in order to execute the necessary machining operations. A setup is identified by three triplets of direction cosines; each triplet defines the position of one axis of the coordinate system of the workpiece with reference to the coordinate system of the machine. Once the setup planning (Contini and Tolio 2004) has been completed, it is possible to execute the pallet configuration activity (Table 10.32) defining the characteristics of the pallet types that will be adopted to process the workpiece types. The process planning provides as output the alternative process plans (Table 10.33) that can be adopted to obtain the demanded workpiece types. Moreover, the FFMS design model needs as input the feasible assignments of machining workingsteps to the types of machines and pallets (Table 10.34).

Table 10.31 Setup planning for product code 240

id setup_face	id workpiece	id workingstep	N parts	cos xx	cos xy	cos xz	cos yx	cos yy	cos yz	cos zx	cos zy	cos zz
sf_1_240	240	ws04, ws05, ws06, ws12	15	1	0	0	0	1	0	0	0	1
sf_2_240	240	ws03, ws11	15	0	0	–1	0	1	0	1	0	0
sf_3_240	240	ws08	15	1	0	0	0	0	1	0	–1	0
sf_4_240	240	ws01, ws02, ws07, ws09, ws10	15	–1	0	0	0	1	0	0	0	–1

N parts = number of parts clamped on the setup face; (cos xx, cos xy, cos xz) = direction cosines of the x-axis of the workpiece coordinate system; (cos yx, cos yy, cos yz) = direction cosines of the y-axis of the workpiece coordinate system; (cos zx, cos zy, cos zz) = direction cosines of the z-axis of the workpiece coordinate system

Table 10.32 Pallet types to process product code 240

id pallet	id setup face	N setupface	N parts
PP01_1_240	sf_1_240	4	60
PP01_2_240	sf_2_240	4	60
PP01_3_240	sf_3_240	4	60
PP01_4_240	sf_4_240	4	60
PP01_5_240	sf_1_240, sf_2_240	2	60
PP01_6_240	sf_1_240, sf_3_240	2	60
PP01_7_240	sf_1_240, sf_4_240	2	60
PP01_8_240	sf_1_240, sf_2_240, sf_3_240, sf_4_240	1	60
PP01_9_240	sf_2_240, sf_3_240	2	60
PP01_10_240	sf_2_240, sf_4_240	2	60
PP01_11_240	sf_3_240, sf_4_240	2	60

Table 10.33 Workplans for product code 240

id workplan	id workpiece	id workingstep	Pallet sequence
Wplan_240_0	240	ws01, ws02, ws03, ws04, ws05, ws06, ws07, ws08, ws09, ws10, ws11, ws12	PP01_5_240, PP01_11_240
Wplan_240_1	240	ws01, ws02, ws03, ws04, ws05, ws06, ws07, ws08, ws09, ws10, ws11, ws12	PP01_1_240, PP01_2_240, PP01_3_240, PP01_4_240
Wplan_240_2	240	ws01, ws02, ws03, ws04, ws05, ws06, ws07, ws08, ws09, ws10, ws11, ws12	PP01_5_240, PP01_3_240, PP01_4_240

Table 10.34 Possible assignments of machining workingsteps for product code 240

id workingstep	id machine	id pallet
ws01	GP, R1, R2, R3, R4, R5	PP01_4_240, PP01_7_240, PP01_8_240, PP01_10_240, PP01_11_240
ws02	GP, R1, R2, R3, R4, R5	PP01_4_240, PP01_7_240, PP01_8_240, PP01_10_240, PP01_11_240
ws03	GP, D1, D2, D3, D4, D5	PP01_2_240, PP01_5_240, PP01_8_240, PP01_9_240, PP01_10_240
ws04	GP, R1, R2, R3, R4, R5, D1, D2, D3, D4, D5	PP01_1_240, PP01_5_240, PP01_6_240, PP01_7_240, PP01_8_240
ws05	GP, R1, R2, R3, R4, R5, D1, D2, D3, D4, D5	PP01_1_240, PP01_5_240, PP01_6_240, PP01_7_240, PP01_8_240
ws06	GP, D1, D2, D3, D4, D5	PP01_1_240, PP01_5_240, PP01_6_240, PP01_7_240, PP01_8_240
ws07	GP, R1, R2, R3, R4, R5, D1, D2, D3, D4, D5	PP01_4_240, PP01_7_240, PP01_8_240, PP01_10_240, PP01_11_240
ws08	GP, R1, R2, R3, R4, R5, D1, D2, D3, D4, D5	PP01_3_240, PP01_6_240, PP01_8_240, PP01_9_240, PP01_11_240
ws09	GP	PP01_4_240, PP01_7_240, PP01_8_240, PP01_10_240, PP01_11_240
ws10	GP	PP01_4_240, PP01_7_240, PP01_8_240, PP01_10_240, PP01_11_240
ws11	GP, R1, R2, R3, R4, R5, D1, D2, D3, D4, D5	PP01_2_240, PP01_5_240, PP01_8_240, PP01_9_240, PP01_10_240
ws12	GP	PP01_1_240, PP01_5_240, PP01_6_240, PP01_7_240, PP01_8_240

10.4 Robustness of FFMS Solutions

The main characteristics of the FFMS configurations have already been studied in Chap. 7 (see Sect. 7.9). It was shown that an FFMS can offer economic advantages if the database of selectable resources is quite heterogeneous. In particular, the profitability of an FFMS compared to a traditional FMS has been investigated for different aggregate demand levels, different part mixes and different types of dedicated machines. The experiments have been carried out considering a deterministic and static production environment, thus simplifying the manufacturing system design model. However, since the preface of this book it was highlighted that the changes affecting the production environment can have an important effect on the design of the most effective manufacturing system solution. Therefore in this section it will be studied if the profitability of an FFMS is affected by the variability of the production problem.

10.4.1 Design of Experiment

The FFMS design approach presented in Chap. 7 (see Sect. 7.4) has been developed to cope with both the dynamic and stochastic characteristics of production problems. The dynamic issues have been addressed adopting a multi-stage approach that considers a multi-period horizon (see Sect. 7.4; Ahmed et al. 2003); the stochastic issues have been faced by modeling the production problem evolution with a scenario tree (see Chap. 5 and Sect. 7.3). The FFMS design problem is addressed by means of the FFMS design model formulated in Sect. 7.6. In this chapter the considered planning horizon consists of two planning periods (these planning periods can be the aggregation of shorter sub-periods). Since the planning horizon consists of only two periods, the multi-stage stochastic model boils down to a two-stage stochastic instance of the problem (Birge and Louveaux 1997). The first planning period must be addressed with the first stage decisions, while the potential changes happening in the second planning period of the planning horizon can be faced with recourse actions, i.e. system reconfigurations.

Chapter 7 has shown that an FFMS solution can offer significant economic benefits compared to a traditional FMS. However, the uncertainty about the future could jeopardize the profitability of an FFMS, because focusing the flexibility reduces the ability of the system to cope with changes in the production problem. To study how an FFMS solution behaves when the production problem is affected by variability, it is necessary to define the scenarios that could happen during the future planning periods; in this case the scenarios are associated with the second period of the planning horizon. The scenarios model the evolution of the production problem and it is therefore important to characterize the changes that could take place. The following issues have been considered to define the types of change:

- The changes of the aggregate demand should be modeled. Herein, the expression “aggregate demand” is always referred to the total amount of cutting time that is required to process all the demanded workpieces. In this way it is possible to precisely express the system capacity needed by the production problem, since different workpiece types could require a different amount of cutting time.
- Product changes that are related to the characteristics (e.g. machining features) of the demanded workpiece types should be modeled.
- The changes should be modeled using the information that can be reasonably provided by a system user to a machine tool builder. In real industrial cases it is not always possible to precisely model the evolution of the production problems. Therefore, the evolution scenarios should be defined by elaborating general (and sometimes imprecise) information provided by the system user.
- The attention should be focused on the key issues that could have an impact on the profitability of an FFMS. Indeed, the customization of the system

resources on the characteristics of the production problem could have negative side-effects if these characteristics frequently change.

Taking into consideration the previous points, the evolution of the production problem can be characterized by answering to the following questions:

- Which is the aggregate demand level (i.e. saturation of the machines) in the first planning period?
- Will the expected aggregate demand remain constant?
- Which is the level of uncertainty related to the future aggregate demand?
- Will the ratio among the operation types remain constant?
- Which is the level of uncertainty related to the future ratio among the operation types ?

The answers to these questions can have a relevant impact on the optimal system configuration that should be designed. Indeed, if the aggregate demand is constant during the planning horizon and the future demand is endowed with a low variability, then only minor reconfigurations will be needed. If the ratio among the operation types remains constant, then it is possible to highly customize the system resources on the production problem. If the fraction of cutting time that cannot be executed on dedicated machines is small, then it should be easier to focus the flexibility of the system.

The answers to the previous questions can be formalized by proposing five factors that characterize the evolution of the production problem. These factors will assume a different value according to the given answers. The following factors have been defined:

- Aggregate demand during the first planning period (*Dlev*).
- Change of the aggregate demand *(Dch)*. The expected value of the aggregate demand during the second planning period is compared to the aggregate demand during the first planning period.
- Variability of the aggregate demand during the second planning period *(Dvar)*.
- Change of the fraction of cutting time required by operation types that cannot be executed on dedicated machines (*Fch*). The expected value of this fraction during the second planning period is compared to the fraction during the first planning period.
- Variability of the fraction of cutting time required by operation types that cannot be executed on dedicated machines during the second planning period *(Fvar)*.

Two values have been considered for each factor: “Level 0” is associated with a low value of the factor, while “Level 1” to a high value. The factors and the values for each level are reported in Table 10.35. To study the influence of each factor on the profitability of an FFMS, all the possible combinations of the values of the factors have been considered, thus leading to 32 experimental conditions to be tested.

Table 10.35 Factors and levels

Factor	N. Levels	Level 0	Level 1
Dlev	2	Low aggregate demand in the first planning period	High aggregate demand in the first planning period
Dch	2	No change compared to the first planning period (+0%)	Increase of cutting time compared to the first planning period (+ 25%)
Dvar	2	Low variability around the expected value. There are three possible outcomes (-10%, 0%, +10%) compared to the expected value	High variability compared to the expected value. There are three possible outcomes (−25%, 0%, +25%) compared to the expected value.
Fch	2	No change compared to the first planning period (+0%)	Increase of cutting time required by operation types that cannot be executed on dedicated machines (+25%)
Fvar	2	Low variability around the expected value. There are three possible outcomes (−10%, 0%, +10%) compared to the expected value	High variability around the expected value. There are three possible outcomes (−30%, 0%, +30%) compared to the expected value

Two stochastic parameters are influenced by the levels of the factors. The first three factors determine the distribution of the future aggregate demand, while the forth and fifth factors determine the distribution of the fraction of cutting time required by operation types that cannot be executed on dedicated machines. For the sake of simplicity, the distributions of the stochastic parameters have been discretized over three values (Table 10.35). The hypothesis is made that these outcomes have the same realization probability.

For each experimental condition it is possible to develop a scenario tree that models both the evolution and the uncertainty. Assuming that there is no correlation between the distributions of the two stochastic parameters, nine scenarios result from the combination of the outcomes. These scenario trees can be generated by means of a tool as presented in Sect. 5.5.

In Chap. 7 it was already demonstrated that the level of aggregate demand influences the profitability of FFMSs, because it has an impact on the size of the system and on the number of resources that are required. It was decided to address production problems requiring a small size system as initial configuration, because this type of systems are more common in industrial cases (see Sect. 7.9.2). Therefore, both levels of the *Dlev* factor require an initial system configuration with two machines for the FMS solution. A low aggregate demand in the first planning period means that the FMS solution is characterized by a low saturation of the machines (65%), while a high aggregate demand leads to a higher saturation (90%).

The fraction of cutting time that cannot be processed on dedicated machines has been set equal to 0.28.

Three test cases have been designed to replicate the Design of Experiment (DoE) and to study which is the impact of the factors on the problem of manufacturing system design. These test cases (named *TC1, TC2* and *TC3*) have been defined by varying the conditions of the production problem during the first planning period and in particular:

- the set of workpiece types composing the part family;
- the ratio between the cutting time required by roughing and drilling operations.

10.4.2 FFMS Profitability

In Chap. 7 the main response of the testing experiments was the profitability of the FFMS solution that was represented by the performance indicator $\Delta cost\%$ (10.1), i.e. the percentage difference between the FMS cost and FFMS cost when the planning horizon consists of only one period. In this section, the performance indicator must be slightly modified to take into consideration also the uncertainty associated with future planning periods. Therefore, the main response of the testing experiments is the expected profitability of the FFMS solution that is represented by the performance indicator $E\Delta cost\%$ (10.2), i.e. the percentage difference between the expected cost of an FMS and the expected cost of an FFMS over the planning horizon. The cost of the system is given by the sum of the initial configuration costs along with the reconfiguration costs that are weighted according to the realization probability of the scenarios. The definition of the performance indicators related to the cost of the system solution are reported in Table 10.36.

Table 10.36 Definition of the performance indicators

Performance indicator	Definition
FMS1	Cost of the FMS solution when the planning horizon consists of one period (single-stage approach)
FFMS1	Cost of the FFMS solution when the planning horizon consists of one period (single-stage approach)
FMS2s	Expected Cost of the FMS solution when the planning horizon consists of two periods (two-stage stochastic approach)
FFMS2s	Expected Cost of the FFMS solution when the planning horizon consists of two periods (two-stage stochastic approach)
$\Delta cost\%$	Percentage difference between the FMS cost (*FMS1*) and FFMS cost (*FFMS1*) when the planning horizon consists of one period (single-stage approach)
$E\Delta cost\%$	Percentage difference between the expected cost of an FMS (*FMS2s*) and the expected cost of an FFMS (*FFMS2s*)

$$\Delta cost\% = \left(\frac{FMS1 - FFMS1}{FMS1} \right) \cdot 100 \tag{10.1}$$

$$E\Delta cost\% = \left(\frac{FMS2s - FFMS2s}{FMS2s} \right) \cdot 100 \tag{10.2}$$

Since there are 32 experimental conditions and three test cases, it was necessary to obtain 96 FFMS solutions and 96 FMS solutions addressing all the production problems in order to calculate the performance indicators $\Delta cost\%$ and $E\Delta cost\%$. As an example the results of Test Case n.1 are reported in Table 10.37.

Table 10.37 $\Delta cost\%$ and $E\Delta cost\%$ for Test Case n.1

ExpCond	Dlev	Dch	Dvar	Fch	Fvar	Test Case	Δcost%	EΔcost%
1	1	1	1	1	1	TC1	13.17	9.66
2	1	1	1	1	0	TC1	13.17	15.38
3	1	1	1	0	1	TC1	13.17	14.66
4	1	1	1	0	0	TC1	13.17	19.81
5	1	1	0	1	1	TC1	13.17	15.58
6	1	1	0	1	0	TC1	13.17	20.69
7	1	1	0	0	1	TC1	13.17	20.72
8	1	1	0	0	0	TC1	13.17	15.36
9	1	0	1	1	1	TC1	13.17	10.01
10	1	0	1	1	0	TC1	13.17	9.20
11	1	0	1	0	1	TC1	13.17	13.88
12	1	0	1	0	0	TC1	13.17	11.51
13	1	0	0	1	1	TC1	13.17	5.56
14	1	0	0	1	0	TC1	13.17	9.20
15	1	0	0	0	1	TC1	13.17	10.39
16	1	0	0	0	0	TC1	13.17	4.08
17	0	1	1	1	1	TC1	17.55	13.48
18	0	1	1	1	0	TC1	17.55	13.85
19	0	1	1	0	1	TC1	17.55	16.18
20	0	1	1	0	0	TC1	17.55	16.57
21	0	1	0	1	1	TC1	17.55	2.03
22	0	1	0	1	0	TC1	17.55	2.52
23	0	1	0	0	1	TC1	17.55	5.56
24	0	1	0	0	0	TC1	17.55	5.96
25	0	0	1	1	1	TC1	17.55	11.32
26	0	0	1	1	0	TC1	17.55	11.10
27	0	0	1	0	1	TC1	17.55	14.37
28	0	0	1	0	0	TC1	17.55	14.81
29	0	0	0	1	1	TC1	17.55	17.50
30	0	0	0	1	0	TC1	17.55	17.44
31	0	0	0	0	1	TC1	17.55	17.44
32	0	0	0	0	0	TC1	17.55	17.44

The impact of the five factors (i.e. *Dlev*, *Dch, Dvar, Fch* and *Fvar*) can be evaluated by means of the dotplots in Fig. 10.15, where the results of the three test cases have been aggregated.

The impact of the five factors on the mean value of *EΔcost%* can be better understood by analyzing also the main effects plots (Fig. 10.16). These graphs allow to compare the mean value of *EΔcost%* that is obtained in correspondence

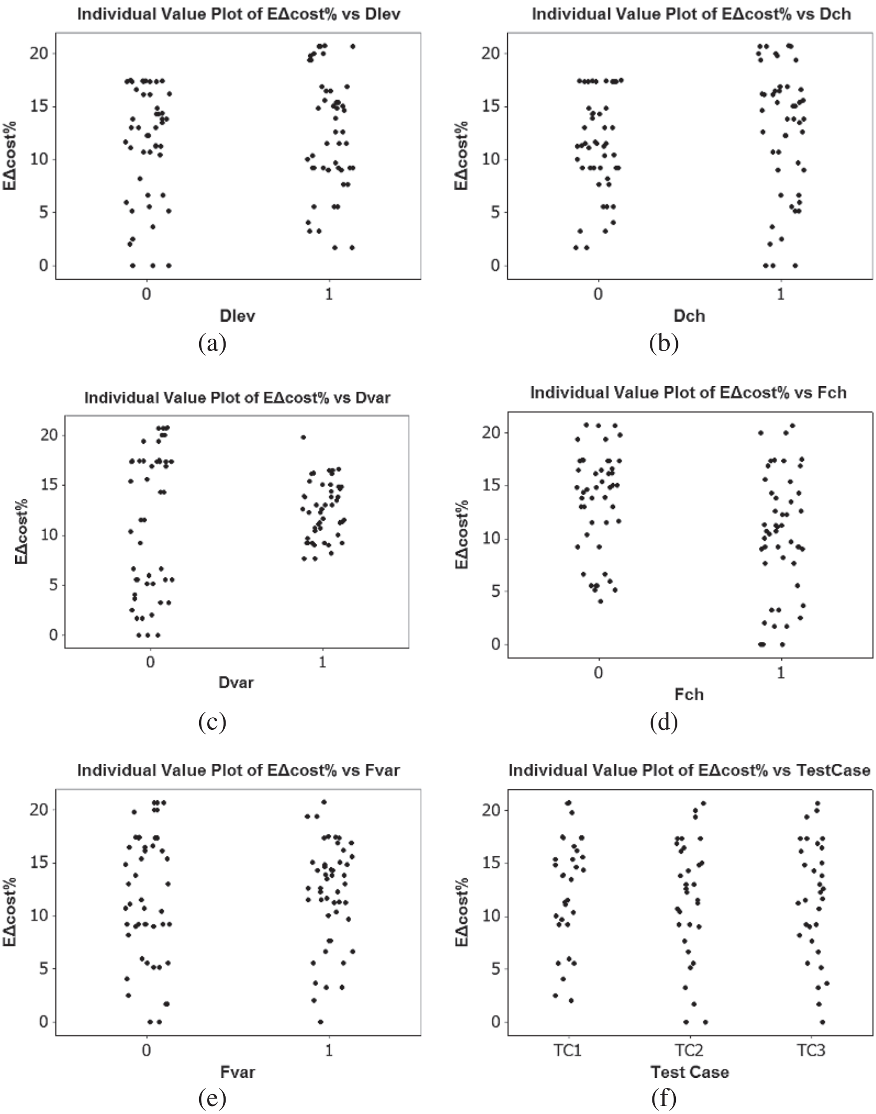


Fig. 10.15 Dotplots of *EΔcost%* against (**a**) *Dlev,* (**b**) *Dch,* (**c**) *Dvar,* (**d**) *Fch,* (**e**) *Fvar* and (**f**) *Test Cases*

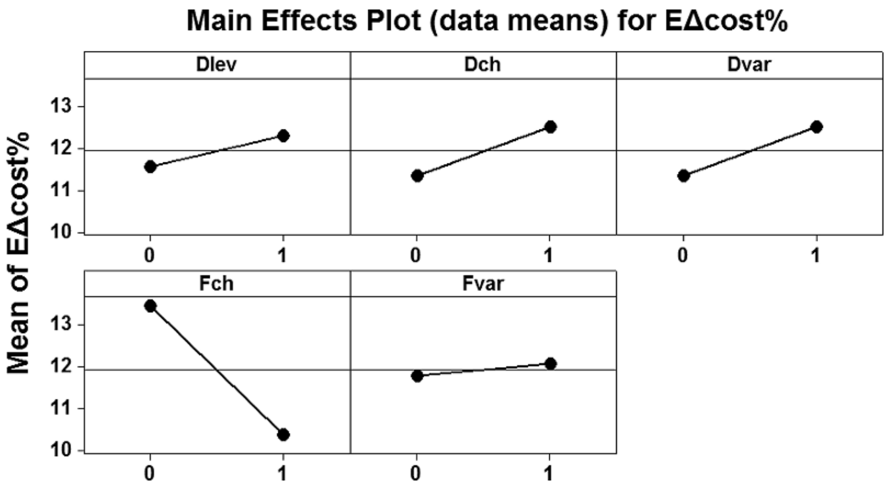


Fig. 10.16 Main effects plots for factors *Dlev, Dch, Dvar, Fch* and *Fvar*

of the different levels of each factor. In this way it is possible to check which is the effect on the value of *EΔcost%* by changing the level of a factor.

The graphs in Figs. 10.15 and 10.16 show that the FFMS solutions are pretty robust towards changes in the aggregate demand. If the initial aggregate demand is high (i.e. factor *Dlev* is at level 1) or if the future aggregate demand tends to grow (i.e. factor *Dch* is at level 1), then FFMS profitability grows as well. Indeed, a higher aggregate demand enables to better focus the flexibility of the system, as it has already been proved in Chap. 7 (see Sect. 7.9.2).

The variability of the future aggregate demand does not have a negative influence on the profitability of an FFMS, since the mean value of *EΔcost%* increases when the factor *Dvar* is at level 1, i.e. when there is a high variability of the future aggregate demand. If the future aggregate demand variability is low, then only minor reconfigurations in the systems will be required and the expected profitability of the FFMS (*EΔcost%*) will not be much different from the profitability of the initial system configuration. On the other hand, if the variability is high, there will be future scenarios with very low aggregate demand and other scenarios very high aggregate demand. In the scenarios with low demand only minor reconfigurations will be needed, thus confirming again the FFMS profitability that is given by the initial system configuration. In the scenarios with a high demand compared to the first planning period, it will be probably necessary to execute major reconfigurations by acquiring new resources; in this case the size of the system grows and it becomes easier to focus the system flexibility. Therefore there will be some scenarios with a higher FFMS profitability and the value of *EΔcost%* will increase compared to the cases with low variability of the future aggregate demand.

Moreover, it can be noted the effect of the factor *Dvar* on the dispersion of *EΔcost%*. If there is a higher variability of the aggregate demand (i.e. *Dvar* at level 1), then there is a lower variance of the expected FFMS profitability, because favorable and non favorable extreme cases will be balanced when calculating the expected value. On the other hand, if there is a low variability of the future aggregate demand (i.e. *Dvar* at level 0), then there is a higher variance of the expected FFMS profitability because it relies mainly on the initial system configuration which can be highly or poorly focused, according to the aggregate demand and on the technological characteristics of the test case (as already shown in Chap. 7 and in this section).

The reduction of the *EΔcost%* variance when the future production problem is subject to high variability can be statistically checked through a F-Test and a Levene's Test. Both tests confirm that there is a significant difference among the variances of *EΔcost%* (Fig. 10.17).

The technological changes of the part family have a greater impact on the FFMS profitability than the changes in the aggregate demand. Indeed, the factor *Fch* influences significantly the mean value of *EΔcost%* (Fig. 10.16) and the expected FFMS profitability is worse when there are changes of high magnitude (i.e. when the factor *Fch* is at level 1). On the other hand, the factor *Fvar* has a small impact on the performance indicator *EΔcost%*.

If the technological requirements of the part family change in the future, then it is more difficult to focus the system flexibility in a stable way because the optimal set of resource types is not constant. It is possible to cope with this problem in two ways:

1. by acquiring more dedicated machines that will have a low saturation, thus highly focusing the flexibility of the system;
2. by acquiring general purpose machines instead of dedicated machines, thus reducing the customization of the system.

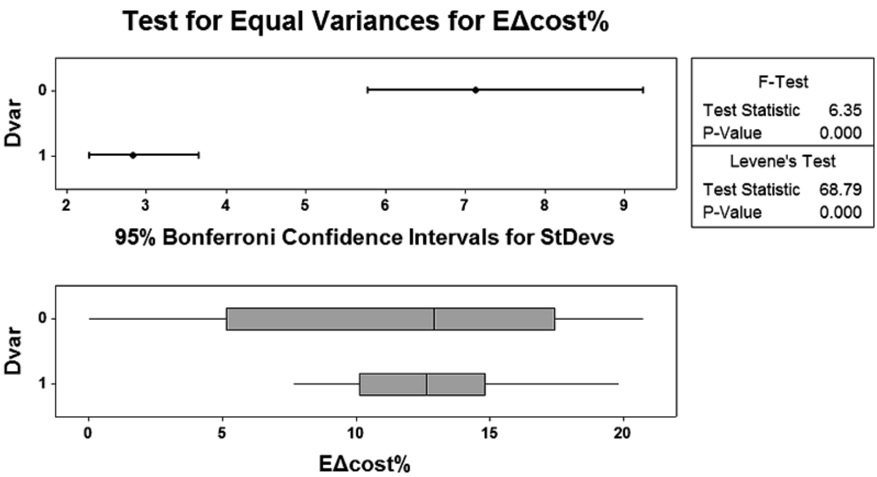


Fig. 10.17 Test for equal variances

In both cases the FFMS solution becomes more expensive, leading to a lower expected profitability of the FFMSs. For instance, considering a sample production problem, the optimal system solution could consist of one general purpose machine and one roughing machine in the first planning period. If the factor *Fch* is at level 1, the amount of finishing operations increases significantly and it could happen that the only general purpose machine is saturated in some scenarios, thus risking not to satisfy the demand. To cope with the problem it is possible to acquire also a drilling machine to reduce the saturation of the general purpose machine by moving some of the drilling&finishing operations. Otherwise, it could be cost effective to change the initial system solution by acquiring two general purpose machines and no dedicated machine. The best solution depends on the cost of the resources and on the realization probability of the scenarios.

The impact of the changes in the production problem on the profitability of an FFMS can be better understood by comparing the FFMS profitability of the solutions given by the two-stage stochastic design model ($E\Delta cost\%$) and by the single-stage design model ($\Delta cost\%$). Moreover, new performance indicators can be calculated to analyze the effect of the changes on the expected cost of the system solutions: *EccFMS%* (10.3) and *EccFFMS%* (10.4). The definitions of these performance indicators are reported in Table 10.38.

Table 10.38 Definition of the performance indicators

Performance indicator	Definition
EccFMS%	Expected Cost of the production problem changes for the FMS solution. It is the percentage difference between the expected cost of an FMS (*FMS2s*) when the planning horizon consists of two periods and the cost of an FMS (*FMS1*) when the planning horizon consists of one period
EccFFMS%	Expected Cost of the production problem changes for the FFMS solution. It is the percentage difference between the expected cost of an FFMS (*FFMS2s*) when the planning horizon consists of two periods and the cost of an FFMS (*FFMS1*) when the planning horizon consists of one period

$$EccFMS\% = \left(\frac{FMS2s - FMS1}{FMS1}\right) \cdot 100 \tag{10.3}$$

$$EccFFMS\% = \left(\frac{FFMS2s - FFMS1}{FFMS1}\right) \cdot 100 \tag{10.4}$$

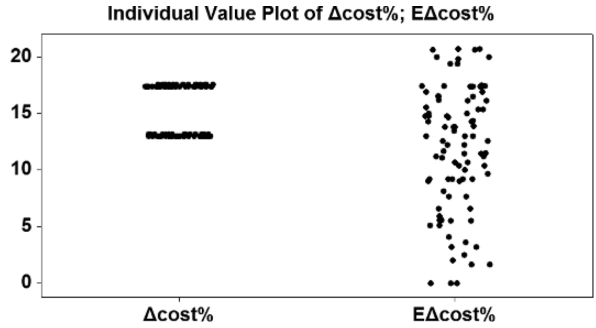


Fig. 10.18 FFMS profitability with a single-period horizon (Δ*cost%*) and a two-period horizon (*E*Δ*cost%*)

Figure 10.18 shows the comparison of the FFMS profitability when the production problem is static and deterministic (Δ*cost%*) and when it is affected by changes and variability (*E*Δ*cost%*). Changes and variability of the production problem increase the variability of the FFMS profitability which is usually lower than in the static case. Given the discrete nature of the resources, Δ*cost%* is concentrated around two values, while *E*Δ*cost%* ranges from 0 to 20.72, as reported in Table 10.39.

Table 10.39 Descriptive statistics of Δ*cost%* and *E*Δ*cost%*

Performance indicator	Sample size	Mean	Standard Deviation	Minimum	Median	Maximum
Δ*cost%*	96	15.253	2.189	13.03	15.27	17.55
*E*Δ*cost%*	96	11.941	5.419	0	12.6	20.72

The cost of the changes in the production problem are shown in Fig. 10.19 by means of boxplot graphs both for *EccFMS%* and *EccFFMS%*. It can be noted that *EccFFMS%* has a mean value slightly higher than *EccFMS%*. This happens because the changes of the production problem have a larger effect on the FFMS solution, since the flexibility cannot be highly focused in all the

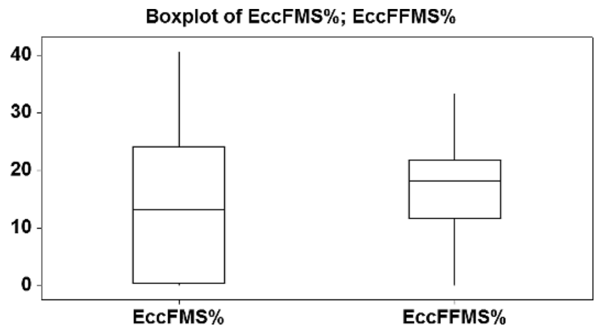


Fig. 10.19 Expected cost of changes for FMS and FFMS solutions

experimental conditions. However, the variability of the change cost is lower for the FFMS solution. Indeed, in the FMS solutions there are extreme cases where the change of the production problem has no effect thanks to the system flexibility, but also other extreme cases with a high cost of the changes given by the relevant cost of a general purpose machine and by the discrete nature of the resources.

The results presented in this sub-section have shown that an FFMS offers a good economic performance when the aggregate demand undergoes changes and is subject to variability in the mid- and long-term horizon. On the other hand, changes in the production problem related to the type of operations that must be executed risk to reduce the profitability of an FFMS solution. In Fig. 10.18 it can be seen that in some cases the expected profitability of the FFMS is very low, and in a few extreme cases it is equal to zero. All these cases are related to experimental conditions where the factor *Fch* is set at level 1, thus meaning that the chance to focus the system flexibility will be reduced in the future. In these cases the FFMS solution is not able to offer any advantage compared to a traditional FMS solution.

10.4.3 Initial System Configurations

The future changes of the production problem have an impact not only on the future reconfigurations, but also on the initial system configuration. Adopting an FFMS design model it is possible to take the decision about the right moment when to acquire system resources. If some changes are expected, it can be effective not to focus the flexibility of the system at the maximum level during the initial system configuration. New performance indicators are defined in Table 10.40: $\Delta initFMS\%$ (10.5), $\Delta initFFMS\%$ (10.6) and $\Delta initcost\%$ (10.7)

$$\Delta initFMS\% = \left(\frac{FMS2sI - FMS1}{FMS1}\right) \cdot 100 \tag{10.5}$$

Table 10.40 Definition of the performance indicators

Performance indicator	Definition
FMS2sI	Cost of the initial system configuration of the FMS solution (two-stage stochastic approach)
FFMS2sI	Cost of the initial system configuration of the FFMS solution (two-stage stochastic approach)
$\Delta initFMS\%$	Percentage difference between the cost of the initial FMS configuration obtained with the single stage approach (FMS1) and with the two-stage stochastic approach (FMS2sI)
$\Delta initFFMS\%$	Percentage difference between the cost of the initial FFMS configuration obtained with the single stage approach (FFMS1) and with the two-stage stochastic approach (FFMS2sI)
$\Delta initcost\%$	Percentage difference between the cost of the initial FFMS configuration (FFMS2sI) and the cost of the initial FMS configuration (FMS2sI), both of them obtained with the two-stage stochastic approach

$$\Delta initFFMS\% = \left(\frac{FFMS2sI - FFMS1}{FFMS1} \right) \cdot 100 \tag{10.6}$$

$$\Delta initcost\% = \left(\frac{FFMS2sI - FMS2sI}{FMS2sI} \right) \cdot 100 \tag{10.7}$$

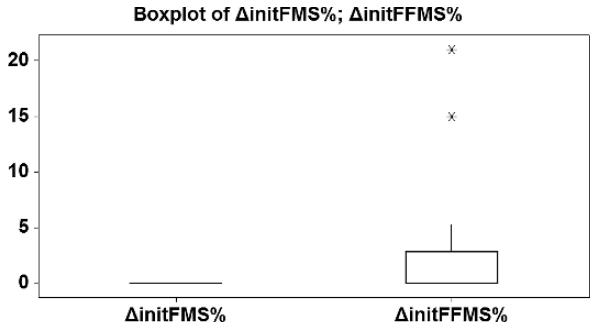


Fig. 10.20 Boxplots of $\Delta initFMS\%$ and $\Delta initFFMS\%$

The testing results in Fig. 10.20 show that the initial configuration of the FMS solution is not affected by the changeability of the production problem. Only the resources that are strictly necessary are acquired and, if necessary, future reconfigurations will be designed adding one or more general purpose machines. On the other hand, the cost of the initial FFMS configuration increases when changes can happen in the production problem. Indeed, the FFMS solution becomes more flexible and similar to an FMS and in some extreme cases it becomes even equal to an FMS. This phenomenon happens when the most critical changes characterize the production problem, in particular when the factors *Fch*, *Dch* and *Dlev* are at level 1. The experimental conditions with $\Delta initFFMS\%$ greater than zero are reported in Table 10.41.

Even if the changes in the production problem could increase the initial investment required by an FFMS, the cost is still lower than the initial cost of an FMS. The values of the performance indicator $\Delta initcost\%$ are shown in Fig. 10.21. The cost reduction of the initial system configuration ranges from 0% to 17.55%, while the expected FFMS profitability ranges from 0 to 20.72%. There are 6 cases where $\Delta initcost\%$ takes value equal to zero. This happens only when there are changes in the technological characteristics of the future production problem, i.e. the factor *Fch* and/or the factor *Fvar* are set to level 1.

Table 10.41 Experimental conditions with Δ*initFFMS%* greater than zero

Exp Cond	Dlev	Dch	Dvar	Fch	Fvar	Test Case	EΔcost%	Δcost%	ΔinitFMS%	ΔinitFFMS%
21	0	1	0	1	1	TC2	0.00	17.37	0.00	21.02
22	0	1	0	1	0	TC2	0.00	17.37	0.00	21.02
22	0	1	0	1	0	TC3	0.00	17.37	0.00	21.02
14	1	0	0	1	0	TC2	1.68	13.03	0.00	14.98
14	1	0	0	1	0	TC3	1.68	13.03	0.00	14.98
13	1	0	0	1	1	TC2	3.23	13.03	0.00	14.98
13	1	0	0	1	1	TC3	3.23	13.03	0.00	14.98
22	0	1	0	1	0	TC1	2.52	17.55	0.00	5.32
18	0	1	1	1	0	TC1	13.85	17.55	0.00	5.32
24	0	1	0	0	0	TC2	5.13	17.37	0.00	5.26
24	0	1	0	0	0	TC3	5.13	17.37	0.00	5.26
23	0	1	0	0	1	TC2	6.60	17.37	0.00	5.26
23	0	1	0	0	1	TC3	6.60	17.37	0.00	5.26
26	0	0	1	1	0	TC2	10.40	17.37	0.00	5.26
27	0	0	1	0	1	TC2	13.03	17.37	0.00	5.26
28	0	0	1	0	0	TC2	13.03	17.37	0.00	5.26
28	0	0	1	0	0	TC3	13.03	17.37	0.00	5.26
19	0	1	1	0	1	TC2	13.83	17.37	0.00	5.26
19	0	1	1	0	1	TC3	13.83	17.37	0.00	5.26
20	0	1	1	0	0	TC2	16.16	17.37	0.00	5.26
20	0	1	1	0	0	TC3	16.16	17.37	0.00	5.26
26	0	0	1	1	0	TC1	11.10	17.55	0.00	3.99
3	1	1	1	0	1	TC2	15.02	13.03	0.00	3.75
3	1	1	1	0	1	TC3	15.02	13.03	0.00	3.75

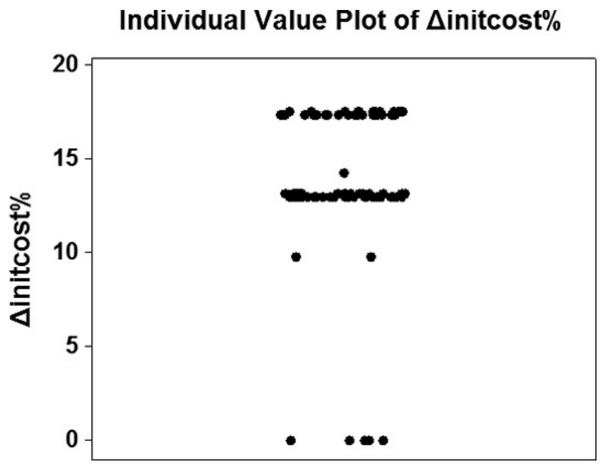


Fig. 10.21 Dotplot of Δ*initcost%*

10.5 Value of the Stochastic Solution

The whole manufacturing system design architecture introduced in Chap. 1 and then detailed in Chaps. 5, 6, 7, 8 and 9 has been developed assuming the importance of taking into consideration the uncertainty affecting the design problem. Therefore, Chap. 5 has addressed the problem of scenario tree generation to model the possible evolutions of the production problem, while Chaps. 7 and 8 have proposed methodologies based on the exploitation of such scenario trees. The aim of this section is to investigate whether it is really worth to invest in modeling the stochastic aspects of the system design problem. In particular, is it possible to quantify the advantage coming from this type of modeling? To answer this question, an extension of the testing experiments presented in Sect. 10.4 has been developed and will be described in this section.

The advantage given by a stochastic approach can be measured by means of the parameter named Value of the Stochastic Solution (*VSS*). This parameter represents the difference between the performance of a stochastic model and the performance of a deterministic model that considers the expectation of the stochastic outcomes (Birge and Louveaux 1997; Terkaj and Tolio 2006; Tolio and Urgo 2007). To compare these models it is necessary to execute the following steps:

- The stochastic FFMS design model (see Sect. 7.6) is solved. The value of the resulting objective function corresponds to the expected cost of the system that can be named *FFMS2s*.
- The determinist version of the FFMS design model is solved. This version of the model takes as input a scenario tree consisting of only one scenario that is built creating an average scenario node in each time period of the planning horizon. However, the solution of this model is not applicable because the decisions are taken not considering the real scenarios.
- The first stage solution of the deterministic model is evaluated against the possible scenarios. For each scenario it is necessary to solve an FFMS design problem that is constrained by the decisions already taken in the first stage. The FFMS costs in the different scenarios are weighted according to the probability of the scenarios to calculate the expected cost of the system that can be named *FFMS2d*.

After solving all the FFMS design versions of the problem, it is possible to calculate the performance indicator *vssFFMS* (10.8) and *vssFFMS%* (10.9). The definitions of these indicators are reported in Table 10.42.

$$vssFFMS = FFMS2d - FFMS2s \tag{10.8}$$

$$vssFFMS\% = \left(\frac{FFMS2d - FFMS2s}{FFMS2d}\right) \cdot 100 \tag{10.9}$$

Table 10.42 Definition of the performance indicators

Performance indicator	Definition
FFMS2s	Expected Cost of the FFMS solution when the planning horizon consists of two periods (two-stage stochastic approach)
FFMS2d	Expected Cost of the FFMS solution when the planning horizon consists of two periods (two-stage deterministic approach)
vssFFMS	Value of the Stochastic Solution when adopting the two-stage stochastic approach to design an FFMS solution
vssFFMS%	Percentage Value of the Stochastic Solution when adopting the two-stage stochastic approach to design an FFMS solution

The impact of the changes in the production problem on the Value of the Stochastic Solution has been evaluated considering the Design of Experiments that has been presented in Sect. 10.4.1.

10.5.1 Testing Results

Considering five factors with two levels (*Dlev*, *Dch*, *Dvar*, *Fch* and *Fvar*) and three replicates (test cases *TC1*, *TC2* and *TC3*) it was necessary to solve 96 times the stochastic and the deterministic versions of the FFMS design model.

The results of the experiments related to Test Case n.1 are reported in Table 10.43 as an example.

Table 10.43 *vssFFMS%* for Test Case n.1

ExpCond	Dlev	Dch	Dvar	Fch	Fvar	Test Case	vssFFMS%
1	1	1	1	1	1	TC1	0.00
2	1	1	1	1	0	TC1	0.00
3	1	1	1	0	1	TC1	0.00
4	1	1	1	0	0	TC1	0.00
5	1	1	0	1	1	TC1	0.00
6	1	1	0	1	0	TC1	0.00
7	1	1	0	0	1	TC1	0.00
8	1	1	0	0	0	TC1	0.00
9	1	0	1	1	1	TC1	5.60
10	1	0	1	1	0	TC1	4.76
11	1	0	1	0	1	TC1	9.67
12	1	0	1	0	0	TC1	7.18
13	1	0	0	1	1	TC1	2.39
14	1	0	0	1	0	TC1	4.76
15	1	0	0	0	1	TC1	7.40
16	1	0	0	0	0	TC1	2.44
17	0	1	1	1	1	TC1	9.24
18	0	1	1	1	0	TC1	0.68

Table 10.43 (continued)

ExpCond	Dlev	Dch	Dvar	Fch	Fvar	Test Case	vssFFMS%
19	0	1	1	0	1	TC1	0.00
20	0	1	1	0	0	TC1	0.00
21	0	1	0	1	1	TC1	2.03
22	0	1	0	1	0	TC1	0.68
23	0	1	0	0	1	TC1	0.00
24	0	1	0	0	0	TC1	0.00
25	0	0	1	1	1	TC1	0.00
26	0	0	1	1	0	TC1	2.25
27	0	0	1	0	1	TC1	0.00
28	0	0	1	0	0	TC1	0.00
29	0	0	0	1	1	TC1	0.00
30	0	0	0	1	0	TC1	0.00
31	0	0	0	0	1	TC1	0.00
32	0	0	0	0	0	TC1	0.00

The impact of the five factors defined in Sect. 10.4.1 is analyzed by means of dotplots (Fig. 10.22) and main effect plots (Fig. 10.23).

The dotplots graphs (Fig. 10.22) show that *vssFFMS%* is equal to zero in most of the experiments (58 off 96 cases). However, there are some cases with a relevant *vssFFMS%* that is close to 10%. The mean value of *vssFFMS%* is equal to 1.744%.

The main effects plots (Fig. 10.23) show that the factors *Dlev*, *Dch*, *Dvar* and *Fvar* have an impact on the mean value of *vssFFMS%*. The impact on *vssFFMS%* is relevant when, given the type of evolution of the production problem, the initial system configuration (i.e. the first stage decisions) plays a crucial role in the performance of the system.

When *Dlev* is at level 1, *vssFFMS%* is higher because the choice of the resources is more critical, since the resources are more saturated. The decisions in the first stage have a strong impact on the need and magnitude of reconfigurations during the future stages. On the other hand, when *Dch* is at level 1, *vssFFMS%* is lower because in the future there will be relevant changes of the demand; therefore reconfigurations will be probably required, thus reducing the importance of the first stage configuration.

The value of *vssFFMS%* grows also when there is high variability of the future production problem, i.e. when *Dvar* and/or *Fvar* are at level 1. Indeed, if there is high uncertainty about the future, then it becomes important to adopt a stochastic approach considering the possible scenarios.

Figure 10.22 shows also that the variance of *VSS%* is greater when there is high variability in the future periods (i.e. *Dvar* and *Fvar* at level 1), as confirmed by the tests for equal variances reported in Fig. 10.24. This means that a high variability of the future production problem has a twofold effect:

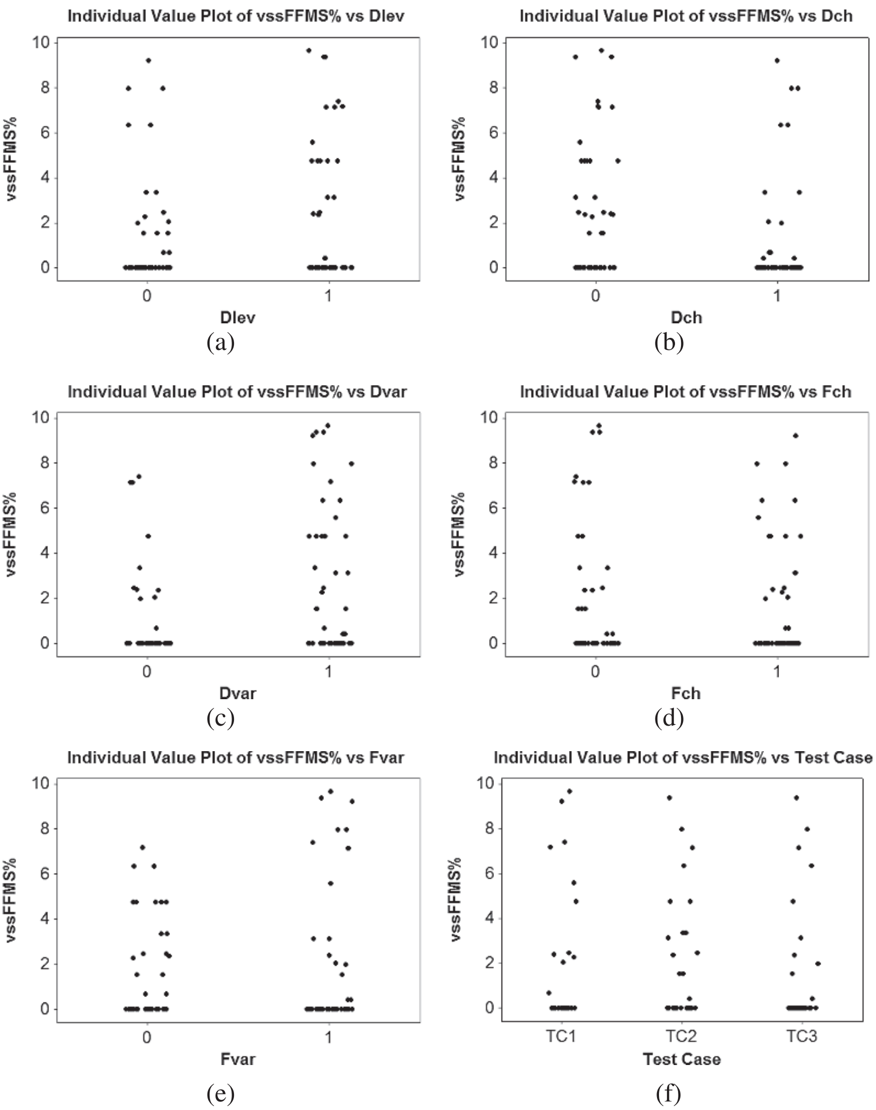


Fig. 10.22 Dotplots of *vssFFMS%* against (**a**) *Dlev,* (**b**) *Dch,* (**c**) *Dvar,* (**d**) *Fch,* (**e**) *Fvar* and (**f**) *Test Cases*

- The mean *VSS%* grows;
- The variance of *VSS%* grows and it is more likely to face extreme cases with a high *VSS*.

The differences among the experimental conditions are reduced if the coefficient of variation (CV) is considered, as reported in Table 10.44.

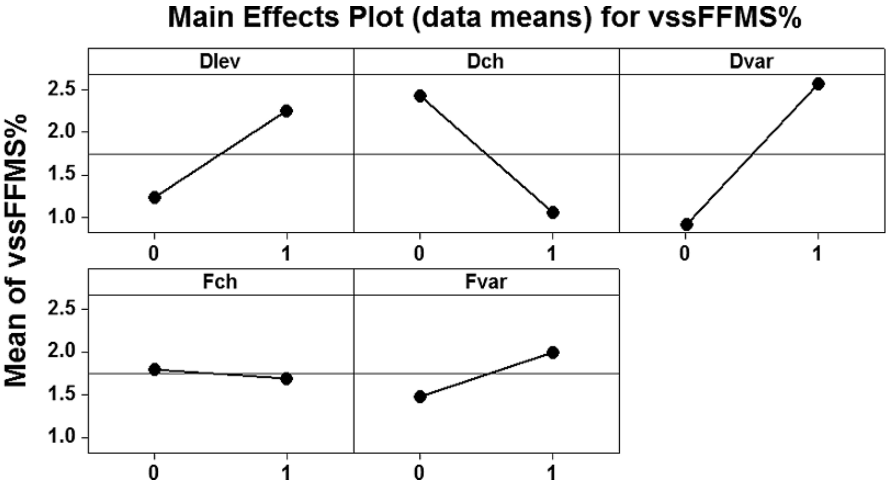


Fig. 10.23 Main effects plots for factors *Dlev, Dch, Dvar, Fch* and *Fvar*

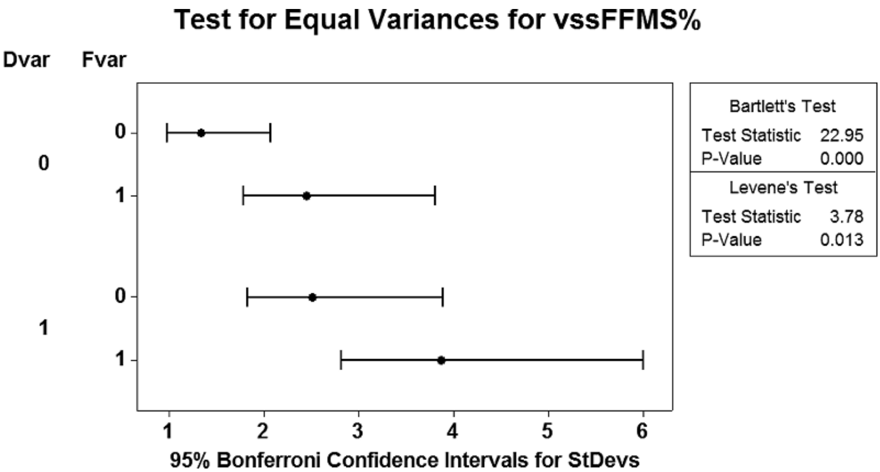


Fig. 10.24 Test for equal variances

Table 10.44 Descriptive statistics for *vssFFMS%*

Dvar	Fvar	Mean	StDev	Minimum	Median	Maximum	CV (mean/StDev)
0	0	0.666	1.334	0	0	4.76	0.49925
0	1	1.171	2.45	0	0	7.4	0.477959
1	0	2.311	2.507	0	1.54	7.18	0.921819
1	1	2.829	3.869	0	0.21	9.67	0.731197

Table 10.45 FFMS profitability with stochastic and deterministic approach

Exp Cond	Dlev	Dch	Dvar	Fch	Fvar	Test Case	EΔcost%	vssFFMS%	EΔcost DET%
11	1	0	1	0	1	TC1	13.88	9.67	4.66
11	1	0	1	0	1	TC2	14.81	9.40	5.97
11	1	0	1	0	1	TC3	14.81	9.40	5.97

Table 10.44 reports that the largest *vssFFMS%* is equal to 9.67%. This means that a stochastic model to design an FFMS can help to avoid wrong decisions that could risk to jeopardize the profitability provided by focusing the flexibility. Indeed the profitability of the FFMS could be strongly reduced (or even become negative in extreme cases) if a deterministic model is adopted. Three examples of this phenomenon are reported in Table 10.45. It can be noted that a stochastic approach gives a profitability (*EΔcost%)* greater that 13%, while adopting a deterministic approach the profitability (*EΔcostDET%*) is severely reduced to less than 6%.

Finally, it can be useful to study which is the impact of the stochastic approach on the cost of the initial FFMS configuration. A new performance indicator *vssFFMSinit%* (10.10) is defined as the percentage difference between the cost of the initial FFMS configuration obtained with the stochastic approach (*FFMS2sI*) and with the deterministic approach (*FFMS2dI*).

$$vssFFMSinit\% = \left(\frac{FFMS2dI - FFMS2sI}{FFMS2dI}\right) \cdot 100 \qquad (10.10)$$

Figure 10.25 shows the dotplot graph of *vssFFMSinit%*. In most of the experiments there is no difference between the initial solution of the stochastic and deterministic approach, since in 58 off 96 cases the Value of the Stochastic

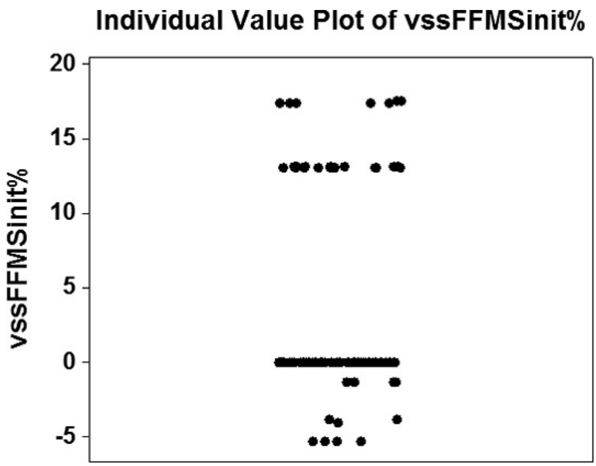


Fig. 10.25 Dotplot of *vssFFMSinit%*

Solution is equal to zero. In 11 off 96 cases the stochastic approach leads to an initial configuration that is more flexible and expensive; the additional investment (maximum 5.26%) is necessary to better cope with the future changes in the production problems and avoid unnecessary reconfigurations. However, it can be noted that in 27 off 96 cases the stochastic approach allows to reduce the cost of the initial FFMS configuration.

The results presented in this section prove that the design of an FFMS requires a stochastic approach in order to carefully evaluate how and when it is possible to focus the flexibility of the system. Indeed, the choice of the methodology to design an FFMS is strongly related to the nature of the system. Since the aim of an FFMS is to focus the system flexibility, it is necessary to adopt a methodology that allows to evaluate which is the amount of flexibility that is required by the present and future production problems. If this evaluation is not carried out, then there is a risk to design poor FFMS solutions that will have a negative economic impact for the system users.

On the other hand, the design of an FMS usually does not require a stochastic approach because it is more difficult to take a wrong decision about the type of machine, since only flexible machines can be purchased. Indeed, in the experiments carried out regarding FMS design the VSS% has resulted to be equal to zero in all the experimental conditions since only one type of flexible machine was available.

10.6 Performance Evaluation Through Simulation

The FFMS design model introduced in Chap. 7 has been developed considering the following approximations:

- failures of the machines have been modeled by introducing an availability coefficient, but the impact could be more relevant if a critical machine fails especially if the FFMS architecture is particularly rigid;
- mission time of carriers cannot be properly estimated ex-ante;
- the dynamics related to the management of the pallets (e.g. queues, waiting time in the buffer zone) have not been considered;
- the management of the cutting tools is not explicitly considered; the saturation of the machines can be reduced if they have to wait for the tools;
- some of the machines could be starved if the necessary work in progress or raw pieces are not ready.

Therefore the resulting system solutions need to be dynamically evaluated (Levantesi et al. 2003; Colledani and Tolio 2005). In particular, it is necessary to evaluate if the various approximations lead to acceptable estimates of the system performance or if the FFMS design model is not reliable.

The attention is focused on the performance of the pallet carrier and on its saturation. Indeed, in production systems characterized by a hybrid architecture, such as FFMSs, the pallet routing is not completely linear. Herein, the estimation of the carrier saturation is extremely important because:

- the number of carrier missions depends also on the dynamics of the system (e.g. queues, failures, starvation, blocking, etc.) that are not easy to estimate and that have been considered in the model only through correction parameters;
- in an FFMS there are more carrier missions than in a traditional FMS because some pallet types can be assigned to more than one machine type. Therefore the carrier could become the bottleneck of the system thus jeopardizing the feasibility of FFMS solutions.

The validation of the FFMS performance has been carried out through the simulation technique (Anglani et al. 2002) adopting the methodology presented in Chap. 9. The design of the testing experiments is introduced in the following sub-section.

10.6.1 Design of Experiments

The experiments have been designed keeping as a reference the general settings presented in Sect. 10.3 for what regards the part family (see Sect. 10.3.1), the machines (see Sect. 10.3.2) and the process planning (see Sect. 10.3.3).

The part mix has been set in order to have a low fraction of operations that can be executed only on general purpose machines (i.e. the fraction of cutting time required by finishing and non-drilling operations), thus helping to focus the flexibility of the system. Four test cases have been defined varying the part family as reported in Table 10.46.

Given the part mix of the test cases, different values of aggregate demand have been considered to evaluate if the size of the system has an impact on the estimate of the system performance. Once again the attention has been focused on small size systems. The lowest value of aggregate demand lead to design an FFMS with two machines (one general purpose and one dedicated machine), while the highest value requires a four-machine FFMS. Twenty demand levels have been defined for each test case, thus leading to 4*20 = 80 experiments.

The value of the critical parameter "mean transport time for a mission of the carrier" (named *tt* in Sect. 7.6.1 and Table 7.4) has been estimated through 50 preliminary tests that have been carried out considering different demand

Table 10.46 Operation type percentages

Test case	Part family	Roughing operation time percentage	Drilling operation time percentage	Finishing and non-drilling operation time percentage
Perf1	260, 271, 282, 502	50%	50%	20%
Perf2	240, 260, 280	50%	50%	20%
Perf3	260, 270, 501	50%	50%	20%
Perf4	240, 260, 280	50%	50%	20%

levels and the operation percentages reported in Table 10.46. The *tt* parameter has been calculated aiming at minimizing the error in the estimate of the carrier saturation. This parameter is critical because it is used in the capacity constraint associated with the carrier resource (see Sect. 7.6.3 and expression 7.23)

The responses of the experiments consist of the estimation and comparison of the following parameters that have been obtained both from the FFMS design model and the simulation model:

- carrier saturation;
- machine saturation.

10.6.2 Testing Results

As anticipated, the carrier could be a critical resource in an FFMS configuration. By plotting the values of carrier saturation as a function of the demand level, it is possible to analyze the estimates provided both by the FFMS design model (*CsatDES*) and by the simulation model (*CsatSIM*). The results concerning the experiments previously described are illustrated in Figs. 10.26 and 10.27, respectively. The results of the replicates (i.e. test cases) have been grouped for each demand level.

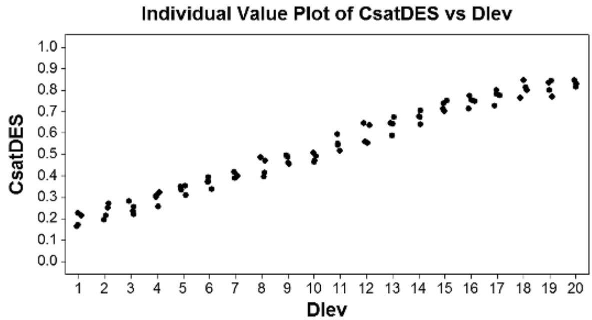


Fig. 10.26 Plot of carrier saturation given by the FFMS design model for each demand level

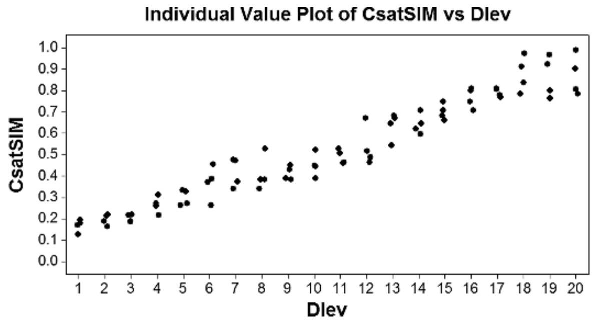


Fig. 10.27 Plot of carrier saturation given by simulation for each demand level

The results show that the level of carrier saturation obtained by the FFMS design model grows almost linearly with the demand level. Moreover, the variability among the different test cases is quite little. Also the saturation given by the simulation grows almost linearly, but it can be noted a higher variability, which is due to the phenomena which have not been considered by the approximations of the design model (e.g. queues, failures, starvation, blocking, etc.).

The results can be better analyzed by calculating the error (*Cerr*) of the carrier saturation given by the design model compared to the output of simulation, which is assumed as the real value. The error is calculated as indicated by equation (10.11):

$$Cerr = CsatSIM - CsatDES \tag{10.11}$$

The graph of the error *Cerr* is shown in Fig. 10.28. It can be noted that the value of *Cerr* slightly grows when the demand value increases. This means that, given the initial estimate of the parameter *tt*, the design model overestimates the carrier saturation when the aggregate demand is low, while it underestimates the saturation when the aggregate demand is high. Since the saturation strictly depends on the mean time of a carrier mission and on the dynamics of the system, this phenomenon can be explained again by the assumptions that have been adopted by the design model:

- The mean mission time has been estimated ex-ante considering a wide range of demand levels. Therefore, the estimate better fits with the demand levels that are in the middle of the considered demand range. However, the mean mission time depends on the size of the system, because, for instance, in a larger system the distance among the resources increases.
- As the saturation of the resources increases, the impact of the dynamics (e.g. queues) that are not considered by the design model increases. For instance, if the machines and the load/unload stations are more saturated, then the pallet buffer will be used more often, thus increasing the number of

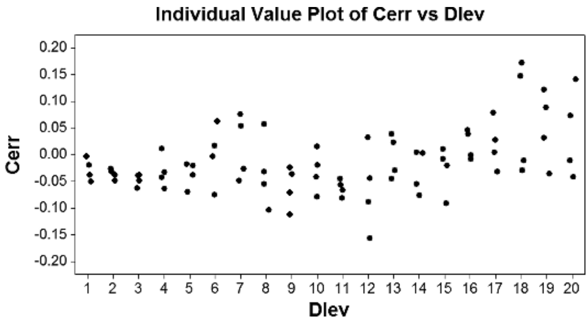


Fig. 10.28 Plot of the error in the estimate of carrier saturation

carrier missions. In the design model this type of missions is not considered and therefore the carrier saturation is underestimated.

It results that the carrier saturation could be better estimated by enhancing the FFMS design model and considering the influence of the size of the system on the performance of the resources. This could be obtained by defining the following values as variables depending on the size of the system:

- the mean mission time (*tt*);
- the reduction of the actual carrier capacity that is caused by missions that are not explicitly considered by the FFMS design model, i.e. missions involving the pallet buffer. This aspect is modeled by the coefficient δ as described in Sect. 7.6.3.

Beyond the analysis of the carrier, it is possible to compare also the estimates related to the machines; in particular, the estimates of the busy time are compared. The busy time of a machine is calculated as the fraction of time during which a pallet is loaded on the working position of a machine. A pallet can be characterized by different states when it is in a busy period:

- the workpieces on the pallet are machined;
- the pallet is not being processed by the machine. This could happen because the spindle is waiting for a tool, or the machine has failed, or the pallet is waiting for the carrier after that it has been completely processed.

Considering the three different types of machine, the following performance indicators have been calculated for each experiment:

- *GPerr*, i.e. the error in the estimate of the busy time of the general purpose machines made by the FFMS design model compared to the simulation output;
- *Derr*, i.e. the error in the estimate of the busy time of the drilling machines made by the FFMS design model compared to the simulation output;
- *Rerr*, i.e. the error in the estimate of the busy time of the roughing machines made by the FFMS design model compared to the simulation output.

The results for the general purpose, drilling and roughing machine are shown in Figs. 10.29, 10.30 and 10.31 respectively. The error in the estimated saturation

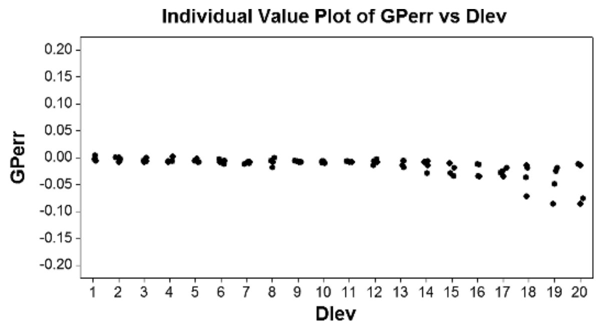


Fig. 10.29 Plot of the percentage error in the estimate of general purpose machine saturation

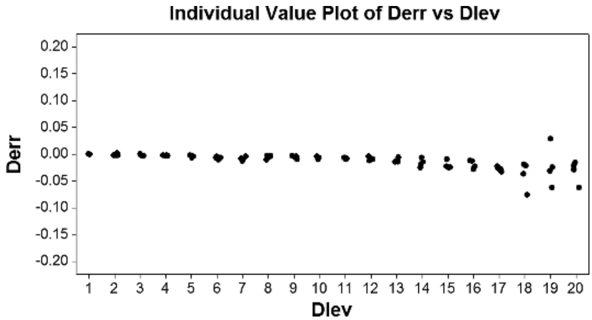


Fig. 10.30 Plot of the percentage error in the estimate of drilling machine saturation

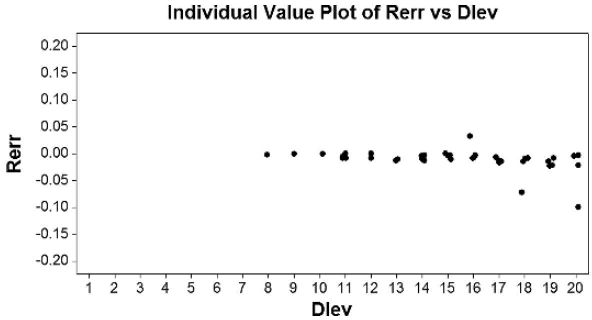


Fig. 10.31 Plot of the percentage error in the estimate of roughing machine saturation

is low for all the machine types (error < 0.1). In particular, the estimate is precise for low-mid levels of aggregate demand. When the production volume grows, the dynamics of the system play a key role, and the machine saturation is underestimated by the FFMS design model. This underestimation is mainly caused by the interaction with the carrier, because when the demand level is high also the number of the carrier missions is high (Figs. 10.26 and 10.27). This means that the pallets on the machines cannot be promptly removed when they are completely processed because of the carrier saturation: therefore the machines risk to be busy even if not working; this phenomenon leads to increase the machine busy time that is underestimated by the FFMS design model.

The few cases where the machine saturation is overestimated (i.e. *GPerr* or *Derr* or *Rerr* are greater than zero), correspond to the cases where the system was not able to completely satisfy the demand because of the saturation of at least one resource. For instance, it happens in the case of a pallet type that must be processed both by the general purpose and by a dedicated machine: if the general purpose machine does not succeed in processing the requested volume of pallets, then the dedicated machine will be starved while waiting for pallets coming from the general purpose machine. As a consequence, the saturation of the dedicated machine will be lower than what expected.

As anticipated, the estimates of the carrier saturation given by FFMS design model can be improved by updating the mean mission time with the output of

Table 10.47 Refining the estimates of carrier saturation

Test Case	Dlev	First launch			Second launch – refining the estimates		
		CsatDES	CsatSIM	Cerr	CsatDES	CsatSIM	Cerr
Perf2	9	0.496	0.385	–0.111	0.398	0.385	–0.013
Perf2	10	0.471	0.393	–0.078	0.393	0.386	–0.007

the simulation model. For instance, the problems corresponding to the demand levels n.9 and n.10 of the test case Perf2 have been solved again by the FFMS design model using as input a new value of the parameter *tt*. The results are reported in Table 10.47. It can be noted that the estimate of the carrier saturation has been improved and the error has been significantly reduced.

10.7 Conclusions

The testing experiments presented in this chapter were mainly aimed at studying the profitability of an FFMS in an evolutionary production context and the effectiveness of a stochastic approach when addressing an FFMS design problem.

The results have shown that the FFMS solutions are quite robust when facing production problems characterized by changes and variability of the aggregate demand. However, when there are relevant changes in the type of operations to be executed, the profitability of an FFMS solution can be strongly reduced, thus increasing the competitiveness of a traditional FMS. Therefore, during the initial phases of the system design it is necessary to analyze the present and potential future production problems in the most precise way.

The stochastic approach to solve the problem of FFMS design has proved to be effective. Even if the mean advantage of the stochastic approach is not high, it gives important benefits in the worst cases by reducing the risk of an FFMS solution. Moreover, it was shown that a stochastic approach can improve the economic performance of an FFMS without requiring a significant increment of the initial system investment cost.

The stochastic approach is required to solve the FFMS design problem because the flexibility can be focused only after a careful evaluation of the possible evolutions of the production problem. Indeed, if the flexibility is not focused (e.g. like in an FMS), then the contribution of a stochastic model is null. Therefore, an FMS copes with the evolution of the production problem through the flexibility of the system, while an FFMS copes with the evolution of the production problem by means of the design methodology and of the focused flexibility of the system.

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Index