Changeable Manufacturing - Classification, Design and Operation

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Abstract

Flexibility and changeability are key enablers for meeting the challenges of a global market. The paper first describes the main change drivers and takes then a deeper look at how changeability in a manufacturing enterprise can be classified and operationalized. The next sections are devoted to changeability in reconfigurable manufacturing systems, assembly systems and factories including buildings and infrastructure. New challenges, perspectives and approaches for process plan reconfiguration as well as for Production Planning and Control are discussed. Finally, the evaluation and economic justification of changeability are addressed and a control loop of changeability is presented.

Keywords

Manufacturing, Factory, Changeability

1 INTRODUCTION

1.1 Influences on Manufacturing

"The world of manufacturing of this century is a networking information world – inside and outside of enterprises and linked to all participants of markets. The fast and global transfer of information and open markets is beside of economic aspects the main driver of changing the global structure of manufacturing." With these statements Westkämper characterizes in short the new paradigm of manufacturing [1].

The left side of fig. 1.1 depicts four major drivers that influence the economy of all industrial nations, whereas the right side highlights the fields in which a dynamic adaptation of industrial production has to take place for a sustainable competitiveness.

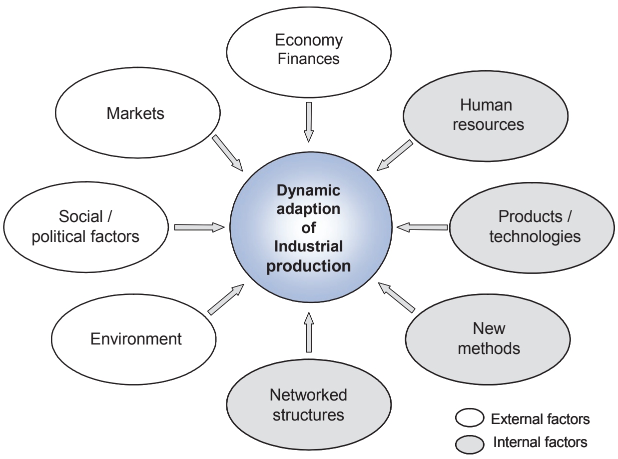

Figure 1.1: Turbulent influences – Dynamic adaptation of manufacturing structures (Westkämper).

Chryssolouris comments: "It is increasingly evident that the era of mass production is being replaced by the era of market niches. The key to creating products that can meet the demands of a diversified customer base is a short development cycle yielding low cost, high quality goods in sufficient quantity to meet demand. This makes flexibility an increasingly important attribute to manufacturing" [17].

One result of the dynamics of markets is the mutation of the product life cycle characteristic and the increasing divergence of the life cycles of the associated processes and equipment, fig. 1.2 [142].

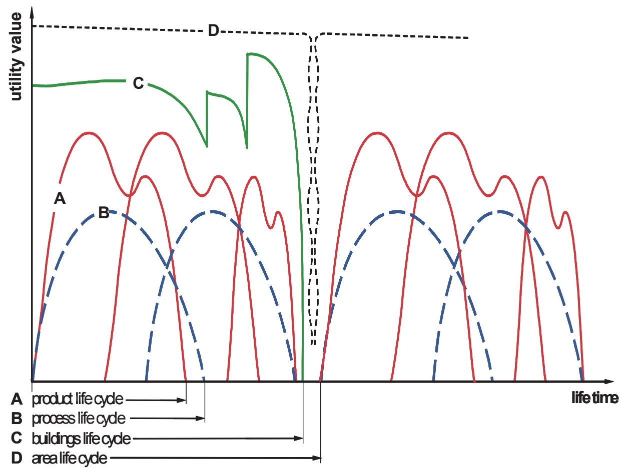

Figure 1.2: Diverging life cycles of the constituent elements of a factory (Wirth).

In the past, we could see a steady volume increase after release of the product, and quite long stable phases followed by a ramp down. Nowadays, product volumes climb much faster to the first peak, then go down and reach a second peak after promotion activities and often a face lift of the product. After that, a sudden reduction of the produced volume occurs mainly because the announcement of a new product.

Not only the new type of life cycles and the exploding number of product models and variants but also increasing outsourcing, manufacturing at different sites and the manifold cooperation in networks increase the complexity of

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production processes. Therefore, for more and more manufacturing companies, the operation of global supply becomes reality. This applies not only to the automobile industry and its suppliers, but also to medium-sized enterprises that serve international markets with high-quality special products. This leads to another fundamental change in the role of manufacturing.

In the past, product development and order handling were regarded as primary processes whereas order fulfillment and distribution were seen more as auxiliary functions. But nowadays, reliable delivery of customized products has the highest priority in globally distributed markets. This priority increasingly determines the development of products, processes and production facilities including logistics.

1.2 Evolution of factories

To meet these challenges factories have undergone several major steps of evolution, which fig. 1.3 depicts with their main features [140].

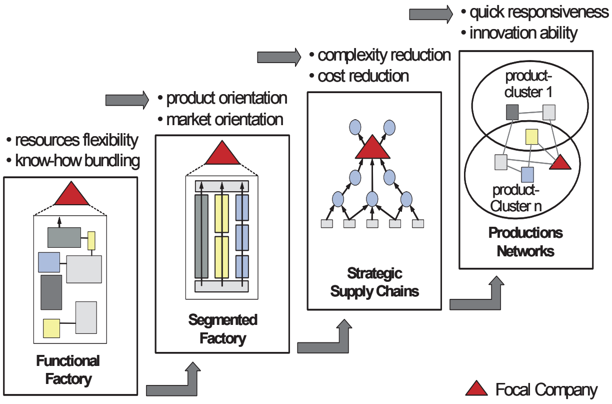


Figure 1.3: Evolution of factories (H-P Wiendahl/ Hernandez).

The *functional factory* with highly flexible resources and know how bundling for specific technologies was quite adaptable to product and volume changes but resulted in long delivery time and high inventory.

With increasing orientation towards the customers need for fast delivery, the *segmented factory* provided an answer in structuring the factory into manufacturing areas, buffers for semi-finished goods and an assembly area. Manufacturing and assembly activities themselves were organised in cells, fractals or segments.

Nowadays we see evolving *production networks* with a temporary cooperation mostly dedicated to the product life of a product family. Here the partners do not have a hierarchical relation although for the customer only one company is visible.

The next generation factories are described as adaptive, transformable, high performing and intelligent. The EU Manufuture strategy underlines this vision in the proposal for the 7th framework (www.manufuture.org).

In addition to the design of the production structure, production enterprises have to fundamentally think over their internal processes. This is frequently done by installing a so called production system, the origin of which is the Toyota Production System [99]. One outcome is the concept of lean production, the central idea of which is to avoid waste in every process with respect to time, space, movement, energy, material etc [144].

1.3 Deriving the objects of changeability

As already stated, production firms have to understand what their main change drivers are and to define necessary and appropriate actions in the appropriate time. One main aspect is to define the objects, which have to be changeable and their appropriate degree of changeability. Fig. 1.4 summarizes the main steps to reach this goal (see also [117] [21]).

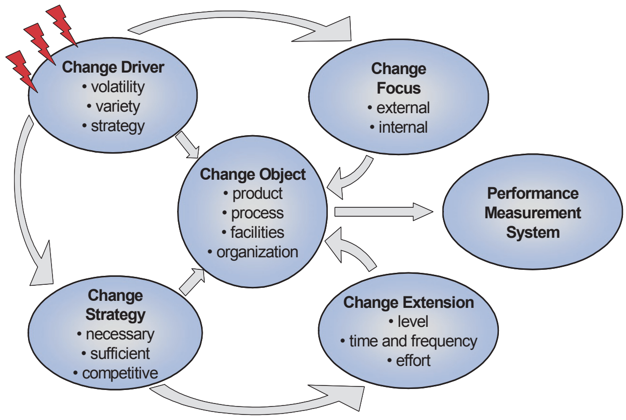


Figure 1.4: Steps to define change objects (H-P Wiendahl).

The impulse for a change is triggered by *change drivers,* whose first category is the demand volatility measured by volume fluctuation over time. Variety is the span width of the products variants both in basic models as well as in variants within the models with respect to size, material and additional features. A major change driver is a new company strategy e.g. to enter a new market, to sell or buy a product line, or to start a turn around program etc. Out of these change drivers two questions arise.

The first is the *change focus*, which can be external or internal. The external focus targets the added value for the customers for instance a product with lower life cycle cost or a faster delivery. The internal focus is typically addressed if the performance of the firm is not satisfactory mainly with respect to profit loss caused by bad organized business processes.

The second question arising from the change drivers is the aspired *change strategy*. Should a change just fulfil the immediate need on the operational level? These changes are more defensive and are typically performed within the given structures and procedures such as the installation or replacement of machines. Or should the changeability be more tactical and fulfil the need of the foreseeable future? These changes are more proactive and occur typically in business processes like order fulfilment or service. Or is finally a strategic investment in changeability chosen with the aim to be prepared for an optional position? [46].

Obviously the selected change potential determines very much the *change extension*. First, the level of the factory on which the changeability has to be ensured, must be determined. Secondly, the expected change frequency and the time allowed for each change has to be estimated and thirdly, the necessary effort in equipment, manpower, knowledge and time, are typically measured as the cost of a change.

Having considered these determinants of changeability the *change objects* can be agreed upon. It can be a product or product family (both can change with respect to type, volume, or mix), technological or logistical processes, smaller or lager part of the manufacturing facilities or the organization of the firm.

Finally a performance measurement system has to be installed in order to measure the impact of the implemented changeability with respect to the output performance of the factory. Typical performance indicators are delivery time, due date performance, turn around rate, inventory, days of supply and overhead cost.

1.4 Constituents of changeable manufacturing

From the introductory paragraphs it became obvious that the scope on the one hand has to be widened from the manufacturing system making various work pieces to the whole factory producing different products in various variants. On the other hand the term flexibilty is very general and must be differentiated according to the factory level. This lead to changeability being an umbrella term and consequently ‘changeable manufacturing’ seems to be appropriate to describe the domain of this paper.

Fig. 1.5 depicts the constituents of such a changeable manufacturing and their specific properties. It is assumed that the product design exists but may also be influenced by the requirements of the physical and logical manufacturing domain.

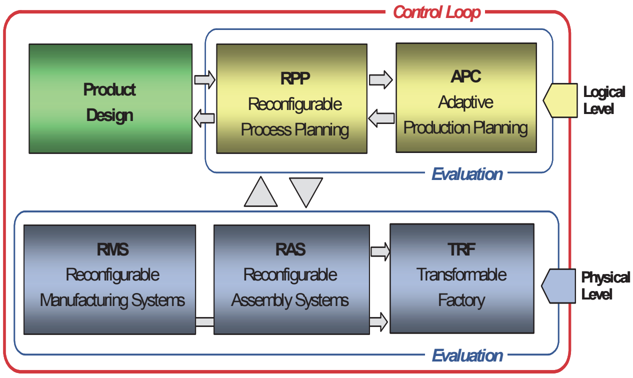


Figure 1.5 Scope of changeable manufacturing (H-P Wiendahl / H ElMaraghy).

On the *physical level* the manufacturing and assembly systems (RMS and RAS) have to be reconfigurable and the factory with its technical infrastructure including building should be transformable (TRF). The *logical level* is necessary to operate a factory and calls for process planning systems able to react to changes in the product design or from the physical level and is therefore called reconfigurable process planning (RPP) [33]. The production planning and control has to react to changes in product volume, mix or reconfigured process plans. Therefore, it is called adaptive production planning and control (APC). A specific additional component is a control loop to monitor external or internal change drivers and to trigger change activities either on the physical or logical level. Finally an evaluation procedure is necessary to justify additional expenses due to the changeability of the physical and logical objects.

The paper will first derive the classification of factory levels and the associated changeability types. Then the aforementioned physical and logical constituents for the design and operation phase will be explained and illustrated with examples followed by the evaluation and measurement of changeability. The control loop to constantly adapt the changeability will be the final topic.

2 CLASSIFICATION OF CHANGEABILITY

2.1 From flexibility to changeability

Tolio comments on the necessity to clearly define the boundaries for flexibilty and reconfigurability when he observes: “Traditionally flexibility is interpreted as the ability of a system to change its behaviour without changing its configuration. Conversely reconfigurability is interpreted as the ability to change the behaviour of a system by changing its configuration. These definitions however can be used only if the boundary of the system is clearly defined. Indeed depending on the border we can interpret a type of changeability as reconfigurability or as flexibility.

Therefore, even if in specific situation it is possible to distinguish between flexibility and reconfigurability it is not possible to define general statements for these characteristics. Therefore it is better to refer in general statements to the term changeability which encompasses the two characteristics [122].

In order to distinguish this ability, in this paper the term changeability will be used as a general term instead of flexibility. *Changeability in this context is defined* as *characteristics to accomplish early and foresighted adjustments of the factory’s structures and processes on all levels to change impulses economically.*

2.2 Factory levels

As already justified the scope of changeability has to be extended to the whole factory. It has been advisable to distinguish not only the levels but also two views namely the resource view and the space view, fig. 2.1. Seven structuring levels of a factory can principally be identified in both views following on the left side a proposal by Westkämper [128] and on the right side a proposal from Nyhuis [97] based on H-P Wiendahl [135].

The *resource view* looks for the technical and human resources, which maintain the processes whereas the *space view* considers the architectural objects which have to be designed in accordance with these resources.

The common ground for both views is given by the underlying *processes,* which are performed by either machines and/or workers. This level is the domain of technology and ergonomics and is beyond the scope of this paper.

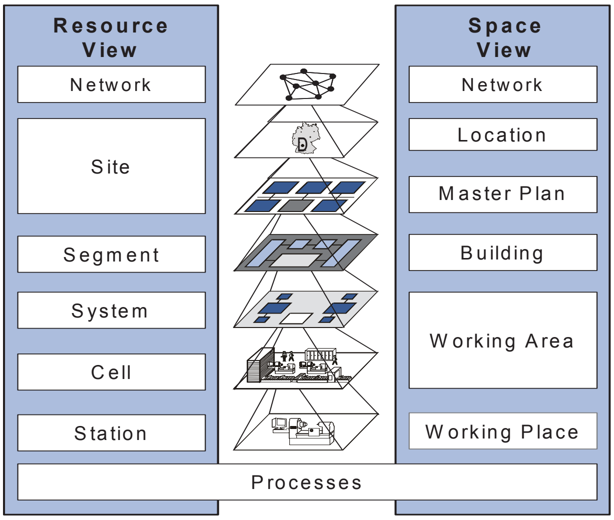


Figure 2.1: Structuring levels and views of a factory (Westkämper, H-P Wiendahl, Nyhuis).

The highest structuring level is the *network* which can be interpreted from the resource view as production units linked by material and information flows along the supply chain respectively, geographical separated sites linked by transportation means acting on traffic ways. Also the network level will not be treated in this paper because the arrangement of that network is more of a strategic task.

The main concern on the level above the processes is on the resource side with the single *workstations* and their value adding operations including workpiece and tool handling. On the space side the ergonomics and safety for the employees at the individual *work places* is the main aspect.

Often several resources are arranged into *cells* that typically perform most of the necessary operations to finish a work piece or an assembly including quality assurance. The operations are executed partly by machines and partly by workers. If the processes are more or less automatically interlinked, the terms manufacturing *system* and assembly *system* are commonly used. Typical classes of manufacturing systems are described in fig. 3.1 and will be treated in more detail in chapter 3, whereas assembly systems are looked at in chapter 4. Cells and systems can be merged in the space view into a *working area*, which describes a zone with the same conditions regarding floor load, height, climate and light and the provision with energy and media (ICT).

The next level up refers to *segments* in which whole products are typically manufactured ready to ship. Segments are commonly structured into manufacturing, assembly, buffers, quality measurement devices, etc. They usually need one or more *building* that also contain technical and staff rooms.

A *site* describes a production unit with more than one product segment and serves as a node of a production network or a supply chain. From the space view a *master plan* is defined describing the general layout of a factory location with the factory and office buildings and necessary infrastructure equipment like energy supply. The location describes from the space view how the site is geographically and politically embedded and connected to the local infrastructure.

2.3 Changeability classes

As already mentioned it seems not advisable to use the term flexibility on all levels of a factory. In addition the level of product to be changed must also be taken into account. If the five structuring levels are combined with the associated product levels, a hierarchy emerges that allows the definition of five types of changeability [135] (fig. 2.2). Any type at a higher level subsumes the types below it.

The hierarchy of product levels start from the top with the product portfolio a company offers to the market. Then the product or a product family follows downwards. The product is usually structured into subproducts or assembly groups that contain workpieces. The workpieces themselves consist of features. The hierarchy of production levels follows the resource view in fig. 2.1. Five classes of changeability evolve from this matrix [31].

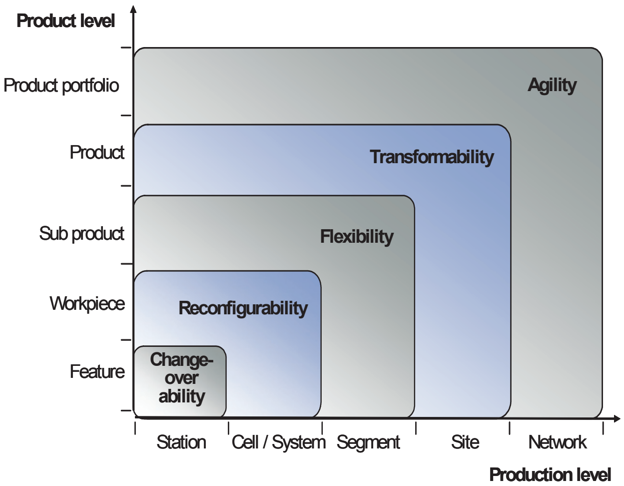


Figure 2.2: Classes of Factory Changeability (H-P Wiendahl).

- *Changeover ability* designates the operative ability of a single machine or workstation to perform particular operations on a known work piece or subassembly at any desired moment with minimal effort and delay.
- *Reconfigurability* describes the operative ability of a manufacturing or assembly system to switch with minimal effort and delay to a particular family of work pieces or subassemblies through the addition or removal of functional elements.
- *Flexibility* refers to the tactical ability of an entire production and logistics area to switch with reasonably little time and effort to new – although similar – families of components by changing manufacturing processes, material flows and logistical functions.
- *Transformability* indicates the tactical ability of an entire factory structure to switch to another product family. This calls for structural interventions in the production and logistics systems, in the structure and facilities of the buildings, in the organization structure and process, and in the area of personnel.
- *Agility* means the strategic ability of an entire company to open up new markets, to develop the requisite products and services, and to build up necessary manufacturing capacity.

In the context of this paper only reconfigurability, flexibility and transformability will be treated further.

2.4 Changeability objectives

Having defined the factory levels and changeability classes the next step is to ask for the objectives a physical or logical component explained in fig. 1.5 of a changeable manufacturing has to fulfill.

For practical purposes it seems advisable to concentrate on three objectives of flexibility as defined by Chryssolouris [17]. Although they are intended to describe the flexibility of manufacturing systems they are also applicable as changeability objectives for assembly systems and the whole factory. Fig. 2.3 gives an overview.

- *Product flexibility* enables a manufacturing system to make a variety of part types with the same equipment.
- *Operation flexibility* refers to the ability to produce a set of products using different machines, materials, operations, and sequence of operations.
- *Capacity flexibility* allows a manufacturing system to vary the production volumes of different products to accommodate changes in demand, while remaining profitable.

Not only technology but also organization and human skills are necessary enablers for all objectives to be achieved.

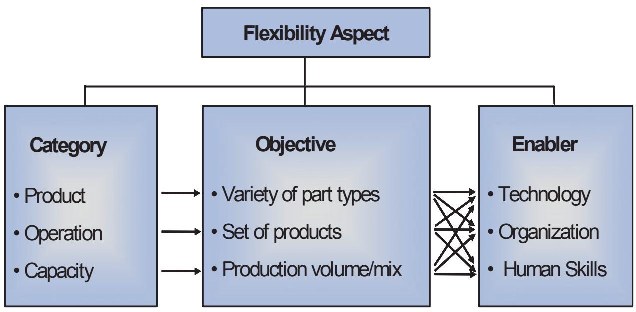


Figure 2.3: Flexibility aspects of Manufacturing Systems (after Chryssolouris).

Chryssolouris discusses the flexibility of manufacturing systems [17], definitions and measurement. He indicates that the quantification of flexibility has been researched extensively in the academia (see e.g. [48] and [20]), but industrial applications have been meagre [4].

These objectives will be discussed in more detail for the manufacturing, assembly and factory level.

Manufacturing level

There exist a plethora of publications on flexibility, the majority of which is devoted to manufacturing flexibility.

Work pieces and part families are produced by manufacturing systems.

Early reviews on manufacturing flexibility can be found in Buzacott and Yao [14], de Toni and Tonchia [22], Sethi and Sethi [114], Koste and Malhotra [70].

Chryssolouris defines flexibility of a manufacturing system as its sensitivity to change and states: "The lower the sensitivity, the higher the flexibility" [17].

A literature survey performed by H. ElMaraghy identifies 10 types of manufacturing flexibility [31]. These are:

- *Machine flexibility*: Various operations performed without set-up change.
- *Material handling flexibility*: Number of used paths per total number of possible paths between all machines.
- *Operation Flexibility*: Number of different processing plans available for part fabrication.
- *Process Flexibility*: Set of part types that can be produced without major set-up changes, i.e. part-mix flexibility.
- *Product Flexibility*: Ease (time and cost) of introducing products into an existing product mix.
- *Routing Flexibility*: Number of feasible routes of all part types/Number of part types.
- *Volume Flexibility*: The ability to vary production volume profitably within production capacity.
- *Expansion Flexibility*: Ease (effort and cost) of augmenting capacity and/or capability, when needed, through physical changes to the system.
- *Control Program Flexibility*: The ability of a system to run virtually uninterrupted (e.g. during the second and third shifts) due to the availability of intelligent machines and system control software.
- *Production Flexibility*: Number of all part types that can be produced without adding major capital equipment.

Assembly level

Eversheim defines five types of flexibility objectives for assembly systems shown in fig. 2.4 [36].

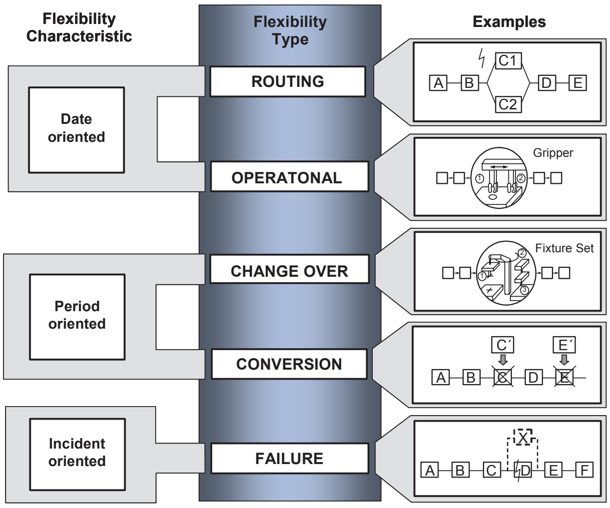


Figure 2.4 Flexibility enablers for assembly systems (Eversheim).

Three characteristics are used to group the flexibility types. *Date-oriented flexibility* has a short timeframe. If product variants change in a line and certain variants need to be processed at specific stations, *routing flexibility* is needed. *Operational flexibility* is necessary when several assembly operations are performed on one object in a sequence in short period of time, e.g. by changing grippers or tools in some seconds.

Period-oriented flexibility has a longer timeframe. This is typically in situations where batches of various products are assembled for hours or even days and a *change-over flexibility* is utilized, e.g. to exchange workpiece carriers. *Conversion flexibility* is very much like reconfigurability. Here, complete workstations are exchanged and replaced, e.g. from automatic stations to manuals stations.

The third characteristic of flexibility is *incident-oriented*. The associated *failure flexibility* aims for a fast reaction if a station has a serious disruption and needs quick replacement of a whole assembly unit.

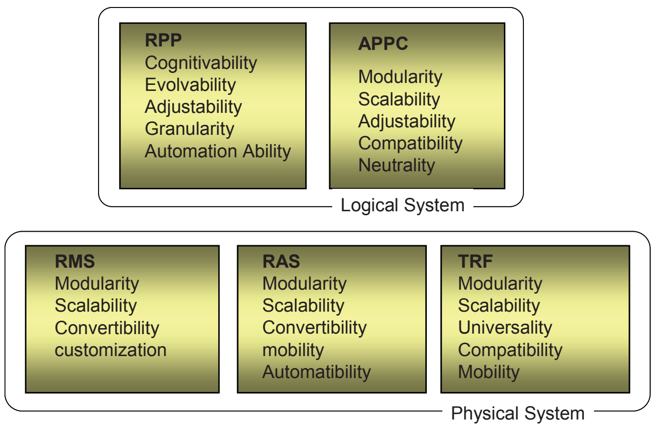
Factory level

On the factory level the changeability objectives include the objectives of the manufacturing and assembly level. But there are more possible change drivers and the necessary extend of change (fig. 1.4) is higher on this level. The following objectives are the most important for a factory:

- *Product transformability* enables a factory to produce a variety of different products.
- *Technology transformability* is the ability to integrate and disintegrate specific product and production technologies.
- *Capacity transformability* allows a variation of the production volumes of each product of a factory.
- *Logistical transformability* enables a factory to respond to new logistical requirements like e.g. the need to deliver just-in-sequence or to deliver different lot-sizes.
- *Transformable degree of vertical integration* is the ability to adapt the degree of added value within the factory e.g. by out or in sourcing of preceding or following production or logistical steps.

2.5 Changeability enablers

A factory that is designed to be changeable must have certain inherent features or properties that will be called *changeability enablers*. They enable the physical and logical objects of a factory to change their capability towards a predefined objective in a predefined time and are not to be confused with the flexibility types or its objectives. Fig. 2.5 gives an overview of the enablers of the physical and logical subsystems of changeable manufacturing explained in fig. 1.5.



RPP Reconfigurable Process Planning
APPC Adaptive Production Planning and Control
RMS Reconfigurable Manufacturing System
RAS Reconfigurable Assembly System
TRF Transformable Factory

Figure 2.5: Enablers of Changeable Manufacturing (H-P Wiendahl / H ElMaraghy).

Manufacturing level

On this level reconfigurable manufacturing systems are assumed to be the appropriate answer to changeability. More details are given in chapter 3. Koren states that in order to achieve exact flexibility in response to fluctuation in demands, an RMS must be designed considering certain qualitative and quantitative properties, the so called key characteristics: modularity, integrability, customization, scalability, convertibility and diagnosability [68] [33] [59] [1] [67]. In the context of this paper they can be interpreted as enablers. These characteristics can be divided into essential and supporting RMS characteristics. Thus the three characteristics customization, scalability and convertibility are seen as essential RMS characteristics while the other ones - modularity, integrability and diagnosability - constitute the supporting characteristics [59]. In addition Koren states: “Modularity, integrability, and diagnosability reduce the reconfiguration time and effort; customization and convertibility reduce cost.”

Assembly level

On the assembly level mainly the same enablers for reconfigurable manufacturing systems are applicable. Two specific enablers should be added. One is mobility, which is important to reconfigure single stations or modules of an assembly system or even to move the whole system to another location. The other one is the ability to upgrade or downgrade the degree of automation. For assembly operations, in contrast to machining operations, there is often the possibility to perform them either manually or automatically. Dependent on various factors like production rate, wage level etc. automatibility allows for adapting the ratio of manual and automated work content.

Factory level

On the factory level the change of objects itself can mainly take place through five so-called transformation enablers. By its existence, an enabler contributes to the fulfilment of a transformation process. Furthermore, the enablers characterize the potential of the ability to transform, and become active only when needed. The characteristics of an enabler influence positively or negatively a factory’s ability to adapt.

Five enablers have been found that the factory planner may use for purposes of attaining changeability in the design phase.

- *Universality* represents the characteristic of factory objects to be dimensioned and designed in their composition for diverse tasks, demands, purposes and functions. This enabler stipulates an over-dimensioning of objects to guarantee independence of function and use.
- *Scalability* provides technical, spatial and personnel extensibility. In particular this enabler provides for spatial degrees of freedom, regarding expansion, growth and shrinkage of the factory layout.
- *Modularity* follows the idea of standardized, pre-tested units and elements with standardized interfaces and also concerns the technical facilities of the factory, (e.g. buildings, production facilities and information systems) as well as the organizational structures, (e.g. segments or function units). Modules are autonomously working units or elements that ensure a high interchangeability with little cost or effort (so called Plug and Produce Modules).
- *Mobility* ensures the unimpeded mobility of objects in a factory. It abolishes the classical division between immobile and mobile things, and covers all production and auxiliary facilities including buildings and building elements, which can be placed, as required, in different locations with the least effort.
- *Compatibility* allows various interactions within and outside the factory. It especially concerns all kinds of supply systems for production facilities, materials and media. It also facilitates diverse potential materials, information and personal relationships. Besides the ability to detach and to integrate facilitates, this enabler allows incorporating or disconnecting products, product groups and work pieces, components, manufacturing processes or production facilities in existing production structures and processes with little effort, by using uniform interfaces.

Reconfigurable process planning level

As shown in fig. 2.5, there are certain key enablers for achieving reconfigurable process plans and commensurate techniques for their efficient regeneration when needed. These are:

Cognitivability: The ability to recognize the need for and initiate reconfiguration when pre-requisite conditions exist.

Evolvability: The ability to utilize the multi-directional relationships and associations between the product features, process plan elements and all manufacturing system modules capable of producing them

Adjustability: The ability and representation characteristics that allow implementing optimally determined feasible and economical alterations in process plans to reflect the needed reconfiguration

Granularity: The ability to model process plans at varying levels of detail to readily and appropriately respond to changes at different levels (e.g. in products, technologies and systems).

Automation ability: The availability of complete knowledge bases and rules for process planning and reconfiguration, accurate mathematical models of the various manufacturing process at macro- and micro-levels, as well as meta-knowledge rules for using this knowledge.

Production planning and control level

The PPC level shows five enablers of PPC changeability (Fig. 2.5).

- *Modularit*y: workable functions and methods or clearly defined objects, e.g. 'plug & produce' modules exist.
- *Scalabilit*y: applicability is independent of product, process, customer and supplier relationship complexity.
- *Adjustabilit*y: design for different demands of the functional logic of order processing, e.g. order generation or release algorithm, and/or weight of the PPC targets.
- *Compatibilit*y: networkability regarding object, method and process, e.g. different IT tools use the same object 'resource' to plan maintenance and production.
- *Neutralit*y: design of the workflow of order processing for different requirements making the definition of the process status independent of the structural and process organization and the enterprise size.

The following chapters will amplify the components of changeability as presented in fig. 1.5.

3 FLEXIBLE AND RECONFIGURABLE MANUFACTURING SYSTEMS

3.1 Manufacturing systems evolution

H. ElMaraghy summarizes the findings from a CIRP-seminar on reconfigurable manufacturing systems regarding their development as follows [31]:

“Manufacturing systems have evolved from *job shops*, which feature general-purpose machines, low volume, high variety and significant human involvement, to high volume, low variety *dedicated manufacturing lines* (DMS) driven by the economy of scale.

In the eighties the concept of flexible manufacturing was introduced in response to the need for mass customization and for greater responsiveness to changes in products, production technology, and markets. *Flexible manufacturing systems* (FMS) were also developed to address mid-volume, mid-variety production needs. Similarities between parts in design and/or manufacture were used to achieve economy of scope. Flexible manufacturing systems anticipated these variations and built-in flexibility a priori; hence they are more robust but have high initial capital investment cost. The flexibility attributes are sometimes underused. In the nineties, optimality, agility, waste reduction, quality, and lean manufacturing were identified as key drivers and goals for ensuring survival in a globally competitive market.

The *reconfigurable manufacturing concept* (RMS) has emerged in the last few years in an attempt to achieve changeable functionality and scalable capacity [67], [69] [42]. It proposes a manufacturing system where machine components, machines, cells, or material handling units can be added, removed, modified, or interchanged as needed to respond quickly to changing requirements.

Such a fully reconfigurable system does not yet exist today but is the subject of major research efforts around the world, with special emphasis on the hardware and machine control aspects. Proponents of this approach believe that it has the potential to offer a cheaper solution, in the long run, compared to FMSs, as it can increase the life and utility of a manufacturing system.

In summary, a reconfigurable manufacturing system is a manufacturing system with customized flexibility and FMS is a manufacturing system with general flexibility”.

3.2 Flexible Manufacturing Systems (FMS)

Traditional manufacturing equipment was mainly dominated by Dedicated Manufacturing Systems (DMS) and Product Specific Machine Tools which are based on fixed automation producing a company’s core products or parts at high volume with low cost per part [68].

As a means of accommodating fluctuations and turbulences in production FMS was developed. An FMS is designed for a possible rapid change in hardware structure as well as in software structure, in order to quickly adjust production capacity and functionality within a part family [33]. An FMS provides generalized functionality (flexibility) for the part-programs [2]. Hence FMS can be conformed to several production requirements [2], they often contain excessive capability which results in unnecessary costs for the customers [73]. Typically, machines used in an FMS are designed to operate in a flexible manner [63].

But they are designed for a defined spectrum of workpieces. Retrofitting to exceed this spectrum can take weeks or months [54]. Because most FMS have more capacity and features than normally used, they are complex and not adaptable enough to changing needs in terms of capacity and gradual changes in functionality [81]. FMS are configurable but not reconfigurable after some years.

3.3 Reconfigurable Manufacturing Systems (RMS)

Current market developments are characterized by imponderability, which mostly cannot be influenced by the companies [81]. They account for 20-30% of the production volume and future increases cannot be excluded. Consequences of this are considerable changes of the planned production which are a challenge for FMS [54].

Koren states that a fast, specific and economic adjustment of the systems regarding structure, capacity, technology and function requires Reconfigurable Manufacturing Systems (RMS) [68] [69] for which he offered comprehensive solutions. Instead of providing a general flexibility through the life time of equipment with built-in high functionality as in FMS, RMS provide customized flexibility [59]. RMS aim at combining a scalable output and an adjustable functionality with a minimum lead time and high productivity [2]. RMS are designed to cope with situations where both productivity and the ability of the system to react to changes are of vital importance [55]. In summary, an ideal RMS comprehends the advances of DMS and FMS [68].

The architecture of RMS can be hierarchically structured as shown in fig. 3.1. On the system level Reconfigurable Machine Tools (RMT) are linked into sequential or parallel production lines [2].

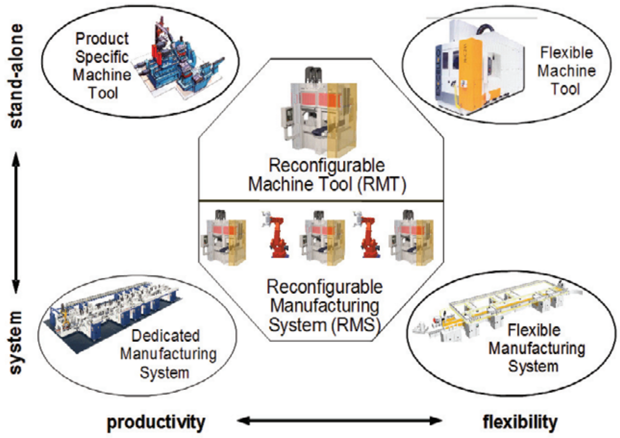


Figure 3.1: Classification of Manufacturing Systems [1].

In recent years, however, two main technologies turned out to be necessary enablers for RMS. In machine hardware Reconfigurable Machine Tools (RMT) and in machine software open-architecture controls are seen as required enablers [68].

3.4 Reconfigurable Machine Tools (RMT)

RMTs seen as essential enablers of RMS are not yet broadly used in manufacturing systems. There exist two main reasons. First, the initial costs for RMT are higher than the investment costs in product specific and inflexible machine tools [3]. The second reason is that the required technology is still in various states of development [33].

For a machine tool being integrated into the manufacturing system, it has to meet demands in quality and in productivity. Furthermore, it has to fulfil requirements concerning kinematics viability, structural stiffness and geometric accuracy [73] [72]. There only exist approaches to improve each of these requirements (e.g. [87] [85]), but a systematic method for configuring RMT starting from functional requirements is still missing [86].

A prototype RMT has been developed by Abele et al., whose concept of a multi technology based reconfigurable machine tool (METEOR) integrates different machining technologies in one machine workspace [3]. Based on a platform, the RMT with his modules can be configured by means of a construction kit. The modules consist of submodules and are also reconfigurable [120]. Fig. 3.2 shows the modular construction kit and possible workspace configurations.

Another example for a prototype RMT is presented by Landers by means of variable RMT configurations to produce different automotive cylinder heads [73].

Besides prototypes, there are no broadly reconfigurable machine tools available yet [61].

In order to achieve many RMS benefits without the RMT, experts from academia and industry suggest parallel investment into re-deployable Non-Reconfigurable Machine Tools (NRMT) [61]. These should be able to be removed and replaced in a short period of time [33].

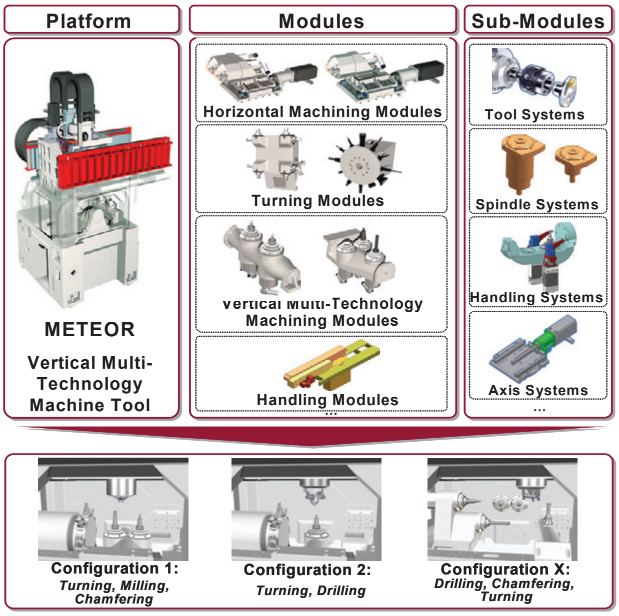


Figure 3.2: Reconfigurable Machine Tool [1].

3.5 Self adapting Control System

Challenges are also imposed on the second main enabler of RMS, the control systems. State-of-the-art control systems can only be configured for a designated mechanical structure; therefore a mechanical reconfiguration requires a reconfiguration of the control system [100]. An approach to cope with these challenges was introduced by Pritschow et al. They described a self adapting control system supported by a reconfiguration method [100]. But systematic tools to achieve truly reconfigurable control systems are still lacking [73].

3.6 Future Prospects

Aside from the mentioned main enablers for RMS - RMT and control systems - there exist further attributes enabling reconfigurability. Koren describes that current time consuming off-line inspection has to be replaced by reconfigurable in-process inspection machines [67].

The concept of reconfiguration as a new manufacturing paradigm has encouraged academic and industrial experts in active research. Recapitulating, Heisel predicts that "reconfigurability is an objective for future machines" [54]. Years ago reconfigurable manufacturing processes were prioritized by international experts as the most important enabling technology for 2020 [90]. Today, most users of non–dedicated systems are satisfied with FMS, which have been known for 30-35 years [54]. Most of them have reluctance to change a running system.

But FMS and RMS possess common grounds in philosophy and application [33]. Stecke predicts that the future Reconfigurable Manufacturing Systems will "be more flexible" [121]. ElMaraghy points out that reconfigurable logical manufacturing support functions and intelligent software are needed in order to realize effective physical reconfiguration [33].

Such an approach is shown in fig. 3.3, which starts out from the idea of a production module that is completely able to work autonomously [28]. It closes the gap between a manufacturing system and the factory and is situated on the segment level.

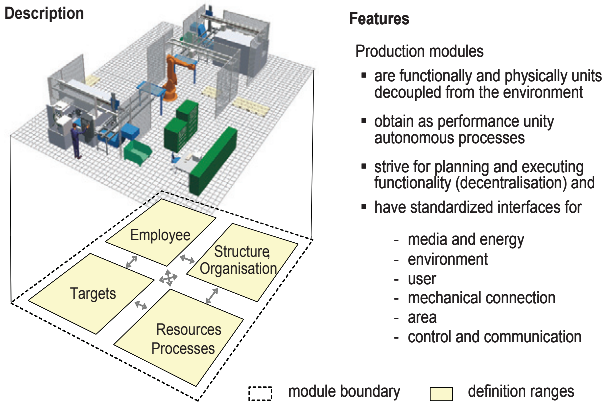


Figure 3.3: Definition of production modules (Drabow).

Besides the real resources for the fulfilment of a process it is also looked at the targets, employees, as well as the inner module structure and the connection to the superior organization. The listed qualities of production modules in the figure make obvious, that the approach has great similarity to the concept of segments, holons or fractals. However, the depicted module aims at allowing a fast reconfiguration of the whole production systems on the shop floor level.

In the future product designers will have to face challenges, too. During an RMS lifetime many different products will be produced and new product designers have to design their products with the structure and capabilities of the manufacturing system in mind [67].

A survey conducted by the ERC/CIRP among experts from automotive and machine tool industry about the importance of various features in manufacturing systems identified a rapid ramp-up as the third ranked important feature [66]. After reconfiguration, every machine has to pass through a ramp-up period in order to re-calibrate the complete system. Therefore, shortening the set-up time of the machine offers important possibilities for improvements [146]. One way to tackle this problem is by using a dynamic real-time machine tool models in combination with real-time capable collision detection algorithms in a Hardware-in-the-Loop Simulation [101].

Besides all technical challenges, human roles in the automation of manufacturing systems have to be considered as probably the most flexible component of a manufacturing system, too [33]. This will impose new challenges considering the design, operation and control of future manufacturing systems. An accurate modelling of human interactions with machines will play an important role in the future evolution of manufacturing systems, for example [32].

However, many open questions remain and several fundamental practical challenges represent fertile areas of research which are listed in detail in [33].

4 RECONFIGURABLE ASSEMBLY SYSTEMS

Flexible assembly systems are easier to realize than flexible and reconfigurable manufacturing systems because accuracy and stiffness requirements are not as high. The supplier industry has offered modular, scalable and mobile assembly systems for many years.

In recent years, the challenge has been more in obtaining volume flexibility with low investment. An interesting approach is the so-called hybrid assembly system in which automatic devices are combined with manual work in one system. With respect to volume, diversity of variants, productivity, and flexibility they are positioned between the manual assembly and automated assembly system [76].

Such hybrid assembly systems are well suited, from economic points of view, for assembling medium numbers of products. Justification for the application of hybrid assembly systems is not only based on the desired production rate, but also on factors such as work content and complexity of assembly operations. Fig. 4.1 illustrates how such a hybrid assembly system might look. In this case the stations are linked with a linear transfer system. Stations can be exchanged within minutes, thereby either adapting the system to another product or changing portions of the system from manual to automatic operation [107].

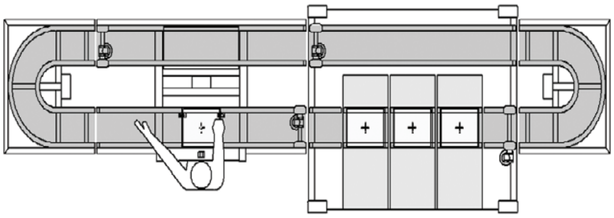


Figure 4.1: Reconfigurable assembly (team technik).

Fig. 4.2 shows an example of a hybrid assembly module in which material transfer is provided by a turntable. In this basic module, one assembly operator is employed. Automatic stations for checking, pressing and greasing supplement the worker's activities. The worker paces the assembly cycle because he triggers the turntable that positions the next assembly in front of him.

If the number of parts to be assembled exceeds the available space to store them in the containers near the worker, a second turntable is installed above the first one, which carries the containers. The system is economical because the movements of the operator are reduced to a minimum and therefore the percentage of non-value-adding secondary operations is minimized.

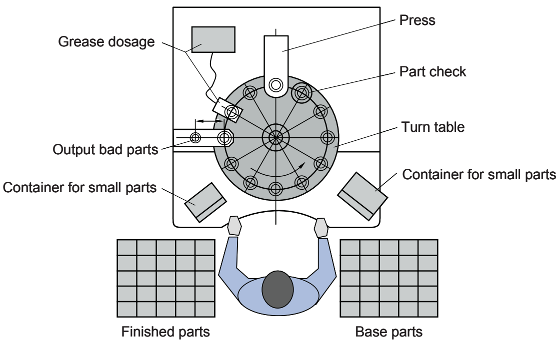


Figure 4.2: Hybrid assembly system with turntable [52].

A special advantage lies in the scalability of the system. This permits expanding output in small construction stages that are achieved on the one hand by automation of single operations and on the other hand by the combination of several modules into a system. Fig. 4.3 depicts the possibilities of expansion in such a system [76].

In the basic construction stage B1, the complete pre and final assembly is carried out manually at a single assembly table. In the next construction stage B2, the screws are inserted automatically using automated stages. At the following construction stage B3, the supplying of the screws is automated using vibration bowl feeders. The cost of assembly using an automated system have been compared with the cost using a modular hybrid assembly system in a specific example [76]. A quantity range between 1,000 and 10,000 products per day had to be covered, and target cost of EUR 0.21 per piece was predefined.

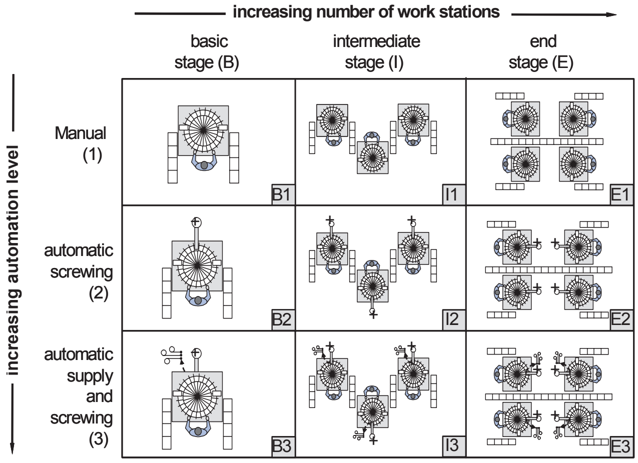


Figure 4.3: Construction stages of an assembly system [52].

Fig. 4.4 shows the corresponding cost curves, which reveal that the automated system reaches the target cost area only at a production rate between 6,000 to 9,500 pieces per day. Considerable additional costs can be expected below these quantities. On the other hand, the modular system, which is expanded by adding assembly cells, reaches the area of the target costs already once the production rate exceeds 2500 pieces per day. When the second cell is installed, the assembly cost remains also close to the target and after the third cell the cost curve is the same as the automated system.

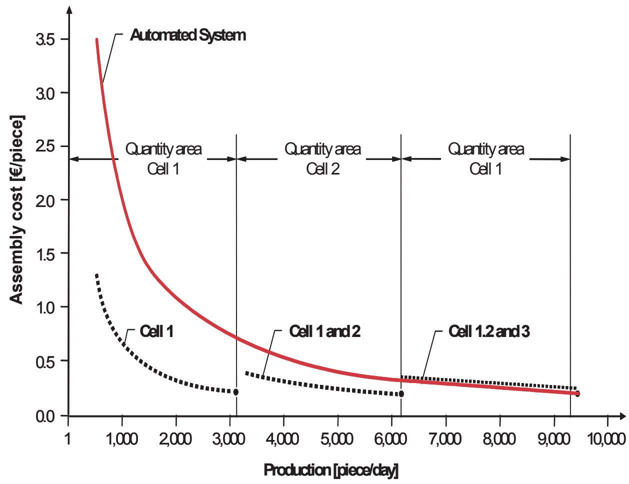


Figure 4.4: Assembly cost comparison for automated assembly system vs. hybrid cells (Lotter; H-P Wiendahl).

Such concepts are particularly suitable for quickly varying products and quantities because:

- The initial investment in the modular system is considerably lower compared with an automated system designed for the final quantity.
- The risk of a bad investment is lower.
- The assembly costs are already in the target area with use of the first cell.
- The development can gradually be carried out in response to actual growth in demand.
- The individual assembly cells can be used differently as demand declines.

5 TRANSFORMABLE FACTORIES

5.1 Factory design fields

The design fields of the factory for planning and achieving the needed changeability are shown in fig. 5.1 [135].

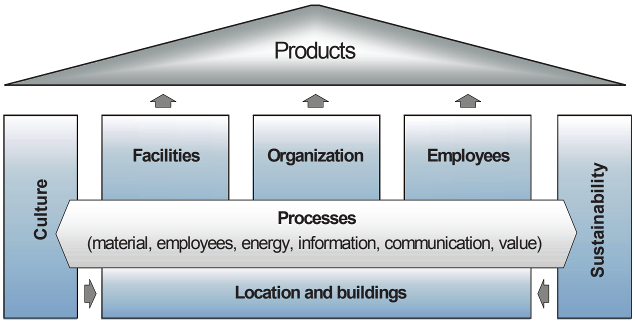


Figure 5.1: Design Fields of Factories (H-P Wiendahl).

The aim of the whole factory must be oriented to serving the market with products. This includes physical products as well as product-integrated services. The main scope of factory design remains the planning of facilities, the organization and the employees. Facilities are comprised of the equipment of all manufacturing and assembly, as well as supporting equipment for logistics and information technology. The organization includes the organizational principles, their processes within the factory and the external interfaces. Labour aspects such as the working environment, the payment system and the working time model are major tasks of the employees design field. The business culture and the increasing importance of sustainability frame these three design fields.

These design fields however, cannot be treated separately. The material, information, personnel, work, energy, media (ICT) and capital flow connect these design fields. The factory location and its buildings are the foundation of the design fields. For this reason, it is especially important to synchronize the design of location and buildings to be well timed with the three main design fields.

5.2 Factory objects

A factory can be defined as “the place of adding value by production with the help of production factors” [126]. The design fields in factory planning (fig. 5.1) show that a factory can be described as a complex socio-technical system consisting of elements or objects. For the purpose of deriving clearly defined objects that are objects of changeability, they can be classified into means, organization and space [97] and allocated according to the structure levels of the factory. The lowest and highest levels are left out because they are outside the scope of factory planning.

With this approach it is possible to segregate and evaluate the objects involved within the factory. Based on the work of Hernandez [57], Wiendahl et al. [141], Nyhuis and Reichardt [98] and Heger [53] all together 261 objects have been identified and aggregated into 25 categories, which are depicted in fig. 5.2.

Other categories are possible as well, e.g. the differentiation between resources, processes and organization as used by Schuh et al. [109].

Producing companies have to react to the turbulence in the environment by changing their factories in ever decreasing intervals. The extent of change necessary today often exceeds the mere possibilities of a single technical system (e.g. a single machine) but has to include related areas as well within a site [104] [136]. This leads to the concept of the transformable factory (fig. 2.7).

Classification / Structuring Level	Means	Organization	Space
Site (Location, Master Plan)	• Provision of Media & Energy - Centers	• Organizational Structure	• Real Estate • Building Development • Outside Facilities
Segment (Building)	• Provision of Media & Energy - Distribution • Information Technology	• Production Concept • Logistics Concept • Structure	• Factory Layout • Structural shape • Girder • Shell • Appearance
System / Cell (Working Area)	• Storage Means • Transportation Means	• Operational Structure	• Finishing
Station (Working Place)	• Production Technology • Production • Equipment • Other Means	• Quality Assurance Concept	• Workplace Design

Figure 5.2: Objects of a factory [53].

In this context reconfigurable manufacturing systems and reconfigurable assembly systems can be seen as a basis for a transformable factory. Examples for such change processes are extension of buildings, the adaptation of the company organization or the relocation of a sub-factory to a low wage country.

5.3 Factory planning

The approach of transformable factories has been treated extensively in research projects [21] [140] [148] [92] [103] and industrial applications [65] [7]. They focus on different phases in the life cycle of a factory. First a factory has to be planned according to the requirements of transformability. This calls for an integrated planning approach regarding the different design fields. In addition, the evaluation of the necessary degree of transformability has to be done and transformable objects have to be created. Finally the transformation process during the life cycle has to be planned as well.

Factory planning can be seen as “a design-process of a factory from the first idea to the start of production that is systematic, goal-oriented, structured in successive phases and supported by methods and tools”[126]. It has to observe several objectives derived from the overall objective of lifecycle productivity [96].

With the growing relevance of the transformability of factory objects the integration of different planning disciplines became more important. Especially compatible solutions for transformability have to be created, e.g. a mobile machine on wheels does not help much if the supply media and power distribution in the building is restricted [57].

Therefore standardized planning processes were developed in order to enable an integrated and continuous factory planning [91] [38] [148]. In addition, the configuration of the planning process for a specific project [39] was subject of research.

Another important approach to enhance the transformability of a factory is the “Digital Factory” defined as “…a super ordinate concept of a comprehensive network of digital models, methods and tools – e.g. simulation and 3D-visualization – which is integrated by a universal data management” [125]. The approaches developed in this area stretch from integrated simulation and visualization tools (e.g. augmented reality (AR) [151]) to a digital support for the distributed and team based planning of layouts [127] [88] [39].

5.4 Evaluation of factory transformability

For the decision of investing in transformability several kinds of costs have to be considered [113] [108]. First, there are the investments for the object at the beginning and in further transformation steps. An example is the investment in a factory building and for planned expansion steps. These investments are routinely considered in the decision, but often other factors are ignored which cover the direct and indirect transformation expenses [111]. Direct transformation expenses are those expenses necessary for the transformation process like special transportation equipment, personnel for the transformation process etc. The indirect expenses consist of additional wages for overtime in order to aggregate a higher stock level of products before a machine is shut down for relocation or the costs for stocking these additional products.

This cost comparison (fig. 5.3) clarifies the necessity to position the factory in a suitable degree of transformability.

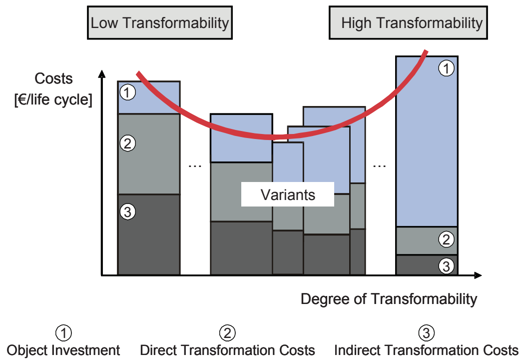


Figure 5.3: Cost comparison of different degrees of transformability [94].

From this necessity three major questions can be derived [138] [108]:

- Which degree of transformability has a specific factory today (actual transformability)?
- What is the required degree of transformability for a factory (target transformability)?
- What is the economic impact of an investment in transformability?

Answers to the first two questions will be discussed in this chapter; a detailed description of the approaches to the economic analysis of transformability is given in chapter 9.

The ability to transform a factory is based on the general change enablers shown in fig. 2.5. These can be combined with the objects of a factory leading to the so-called transformation building blocks. They consider a specific attribute of an object and can therefore be used as a basis for the evaluation of actual and target transformability. Example of these transformation building blocks includes the scalability of a layout or the universality of an IT-system within the factory.

Based on these transformation building blocks a seven-step procedure for evaluating the transformability of a factory and deriving measures for action was developed by Wiendahl, Heger and Nyhuis [97] [139].

It starts with a factory analysis (step 1) to quantify the actual transformability. For this purpose, quantitative and qualitative features were developed that allow an assessment of the transformability of each individual transformation building block and therefore each factory object (step 2).

Based on scenarios, which have to be developed for the factory, the most important transformation objects are identified (step 3).

This identification is supported by a so-called transformation portfolio in which change depth and change variance of the objects form the axes, fig. 5.4. The relative change depth quantifies the total degree of change necessary as predicted by the different scenarios. The change variance is the variance of the necessary degree of change for a single object in the different scenarios.

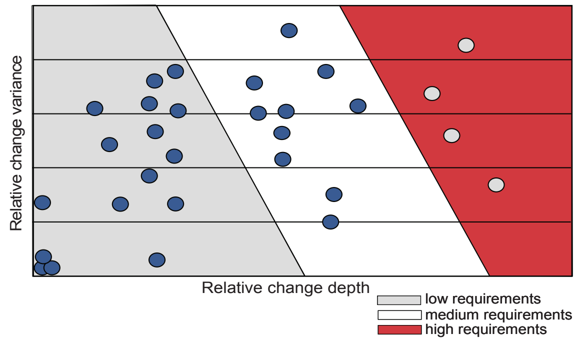


Figure 5.4: Transformation Portfolio of Factory Objects [96].

The transformation objects falling into the segment of the portfolio with high values on both scales have high transformation requirements and need attention for further analysis.

Subsequently scenarios (step 4) are developed and the requirements profiles (step 5) and the target transformability for those relevant transformation objects (step 6) are derived. Finally, measures to elevate the factory to the desired degree of transformability (step 7) are recommended. These recommendations should to be evaluated from an economic perspective afterwards.

The results of the procedure can be shown as transformability profiles for the single factory objects. The example in fig.5.5 shows the actual and the target transformability of the most important transformation objects of a real case.

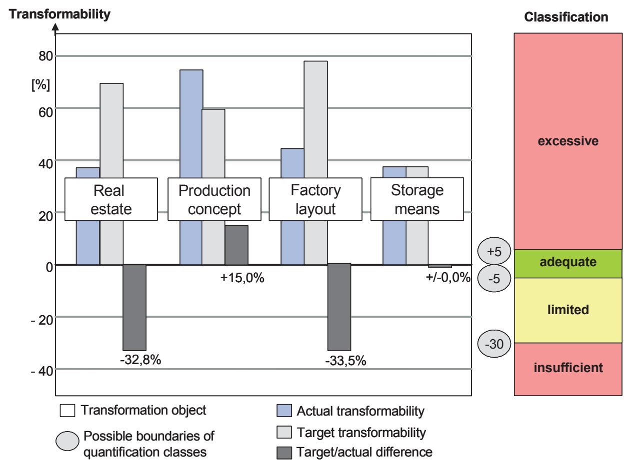


Figure 5.5: Example of transformability profiles [97].

The target degree of transformability is for all objects less than 100% because of the specific environment of the factory. The classification thresholds were derived from project experience and can be set as necessary.

Several other methods for evaluating flexibility or transformability with different focuses have been developed (see among others [37] [47] [40] [113] [49] [111] [108]).

5.5 Approaches to transformable factories

The approach of transformable factories has not only gained interest in research but also widely in industrial practise.

Especially solutions that combine modular and mobile aspects have been realized in different areas. One example is the so called "Mobicell" developed from BMW [89]. A Mobicell is a production module, which consists of a steel-frame, on which a robot, material handling and the required control equipment are assembled. The module is mostly self-contained, transportable and has standardized interfaces. Therefore, it can be easily used in different locations during its life cycle and enhances the changeability of the enterprise as a whole. The term plug & produce was introduced to describe this capability [35].

In terms of building equipment the media and power distribution within a factory building or an area has gained wide interest. If work stations or other equipment, that need media connection, are relocated frequently, like manual assembly stations, the media distribution can be designed as a grid. The media network is hung from the ceiling and can be easily accessed by the workers themselves at every location within the building [95].

An example from the area of organisation is the concept of transformable working hours where the working hours can be adapted to the market demand on a daily basis [74].

5.6 Example of a transformable factory

The Modine Wackersdorf GmbH in South Germany is a supplier of thermal management products especially radiators for the automotive industry. When the company received a five-year-contract with an OEM the original building was too small for installing the required capacity. Therefore a green-field factory planning project was initiated. The requirements were an expected growth of production volume and number of variants by 110% over the next five years. The future after those five years was uncertain. Therefore, the new factory was planned on the principles of synergetic factory planning [98] and with a special focus on transformability.

The resulting factory is able to react to changes in the environment in many different ways. Fig. 5.6 illustrates two examples. The assembly stations are mobile and can be relocated where it is needed within hours. The building and the layout enable a growth of the different production departments as needed.

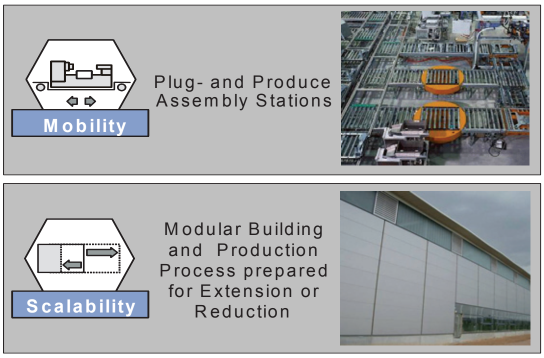


Figure 5.6: Examples for transformable factory elements (courtesy Modine Wackersdorf Germany).

This is achieved by means of a modular building (e.g. panels, offices, piping, and cladding) and modular processes (e.g. autonomous teams, plug-and-produce equipment). The media distribution covers all areas of the factory via the ceiling and therefore imposes no restrictions on the layout and during relocation of equipment.

Fig. 5.7 gives an impression of the building structure. It consists of two modules each of it has 2 sub-modules with a span width of 36 respectively 18 meters. Each module is autonomous with regard to media and energy supply. The building can be expanded by two further modules if necessary without interruption of the production.

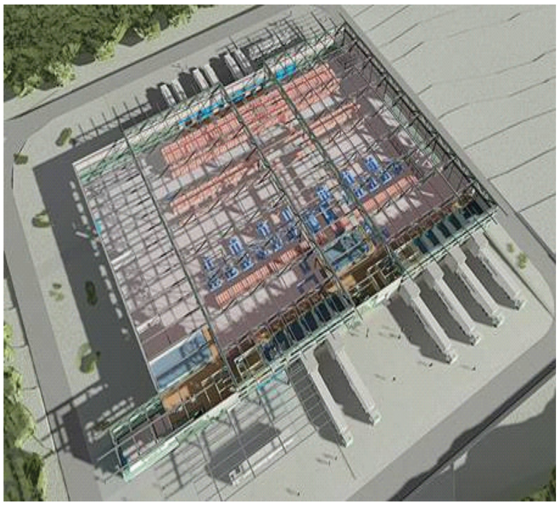


Figure 5.7: Layout of the factory building (Reichardt).

The high grid width supports the transformability in the building. Besides the technical basis the workforce had a strong will to adapt and change. All these aspects lead to a highly transformable factory [13] that was awarded as "best assembly" in Germany 2006.

This example does not mark the end of the factory evolution. In some cases even temporary factories have been installed e.g. to assemble streetcars in only 6 months.

To utilize the transformability fully changeable process plans and production planning and control are also needed if necessary. These aspects are further treated in the next two sections.

6 RECONFIGURABLE PROCESS PLANS FOR CHANGEABLE MANUFACTURING SYSTEMS

6.1 Introduction

Process plans and planning functions form an important link between the features of generations of products / product families and the features, capabilities and configurations of manufacturing systems and their modules throughout their respective life cycles. The paradigm shifts in manufacturing systems, and their increased flexibility and changeability, present both challenges and new degrees of freedom in achieving cost-effective adaptability. They require corresponding responsiveness in all support functions including process planning, which is one of the 'soft' or 'logical' enablers of changeability in this new environment. It is increasingly important that all support functions, both at the physical and logical levels, are usable across several generations of product families and manufacturing systems. These must not only be in place but also be adaptive and well integrated at many levels for any successful and economical responsiveness to changes in manufacturing to materialize.

6.2 Classification of Process Planning Concepts

Manufacturing process planning seeks to define all necessary steps required to execute a manufacturing process, which imparts a definite change in shape, properties, surface finish or appearance on a part or a product, within given constraints, while optimizing some stated criteria [30]. Several approaches for process planning were developed to suit given production scenarios such as [50] [152], optimize processes sequence [15] [16] [19] and parameters [77] [115] capture their non-linearity [11] [18] [58] and recognize the mapping between parts' features and machines capabilities [116].

The various process planning concepts and approaches, are best classified, as follows, based on their level of granularity, degree of automation, and scope [33].

Multi-Domain Process Planning is the highest level. It seeks to select the most suitable manufacturing domain or technology for production. It has seen little automation to date. Macro-Process Planning selects the best sequence of multiple different processing steps and set-ups as well as the machines to perform them. Micro-Process Planning details each individual operation and optimizes them to determine the best process parameters.

There are several automation levels including Manual, Computerized (CAPP) and Automated Process Planning, which is further classified according to the type and degree of automation as:

Retrieval / Variant Process Planning

The fundamental concept is that parts that bare similarity in design or manufacturing features are grouped into part families, a unique Group Technology code is generated for each part, a composite part that contains all the features in the family, and a standard optimized master process plan for each family of parts are developed beforehand. The planning of a new part is performed by identifying, retrieving and modifying existing plans for similar parts, using the GT code.

Semi-Generative Process Planning

In semi-generative process planning, the 'standard master process plan' concept is *augmented* by algorithms capable of making some '*part-specific*' decisions about the operations and their parameters. It combines both retrieval and algorithmic procedures assisted by CAD models, databases, decision tables or trees, heuristics and knowledge rules. This allows process plans to be partially customized for new features.

Generative Process Planning

Totally generative process planning aims at generating optimized process plans from scratch given sufficient input about all relevant data. It relies heavily on using complete and accurate models of the parts and processes, and their behaviour, constraints and interactions as well as automated reasoning and knowledge representation and use. A truly generative process planning system in any domain is yet to be realized.

Distributed, Web-based, Networked Process Planning

A trend is emerging for distributed and more decentralized process planning systems, both logically and physically. There are a number of factors that motivate this trend including the globally distributed manufacturing facilities, the wide spread use of the Internet, and the application of agent-based techniques.

6.3 Evolution of Manufacturing Systems and Products

Evolution of Systems

Flexible manufacturing was introduced for mid-volume, mid-variety production to achieve greater responsiveness to changes in products, production technology, and markets. Similarities between parts in design and/or manufacture, and the concepts of static pre-planned Product Families and Group Technology were used to achieve the economy of scope.

Hardware reconfiguration in RMS where modules may be added, removed, modified, or interchanged as needed to respond to changing requirements also requires fundamental changes in the software used to control individual machines, complete cells, and systems as well as to plan and control the individual processes and production [31].

Evolution of Products

The evolution of parts and products is driven by customer demands, innovation, availability of new knowledge, technology and materials, cost reduction, environmental concerns, and legal regulations. Derivatives and variations in function, form and configuration lead to products classes. This leads to a *changeable product family* that should capture variants of the product, its components and their configuration over their life cycle.

Static Parts/Products Families

The classical notion of a parts/products family was established in conjunction with the concept of Group Technology where members of the family have similarities in the design and/or manufacturing features. Flexible manufacturing systems relied on this definition of pre-defined parts/products families with non-changing borders to achieve the economy of scale by pre-planning the manufacturing system flexibility according to the defined scope of variations within the family. In this case, a '*Composite part*' that contains all features of the family members, which can be considered and a '*Master Process Plan*', is devised and optimized in anticipation of the pre-defined variations, for use in '*Variant Process Planning*' and other manufacturing related activities. The cylinder block of an automobile engine is an example of a product family with well-defined and pre-planned boundaries, where variations in the number, orientation, size and characteristics of cylinder bores, as well as size, mounting bosses, oil gallery, bolt holes, etc. result in different members of the family such as V6, V8 and V10 cylinder blocks for different vehicles.

7 EVOLVING PARTS/ PRODUCTS FAMILIES

In the current dynamic and changeable manufacturing environment, the products are frequently changed and customized, and it is possible to reconfigure the manufacturing systems as needed and when needed by changing their modules and hence their capability and capacity. Therefore, the notion of constant parts/products families is changing. This presents new challenges for related activities such as process planning.

A new class of '*Evolving Parts/Products Families*' has been proposed by H. ElMaraghy [33]. Since adding, removing, or changing manufacturing systems' modules changes its capabilities and functionality, the reconfigured system would be capable of producing new product features that did not exist in the original product family. This allows it to respond to the rapid changes in products, their widening scope and faster pace of their customization. The features of new members in the evolving families of parts overlap to varying degrees with some existing features; they mutate and form new parts instances and different members or families as shown in fig. 7.1.

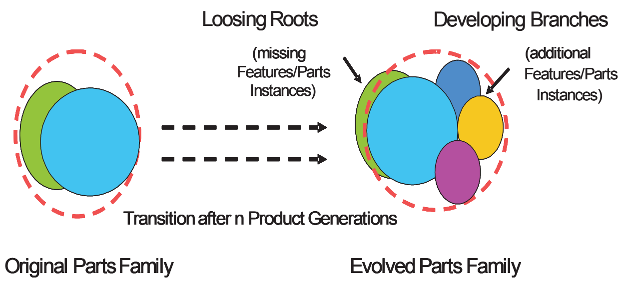


Figure 7.1: Evolving parts and products families (H. ElMaraghy).

This evolution occurs either *chronologically* due to gradual changes in technology and knowledge or *functionally*, which is caused by a significant and major change in requirements.

In summary, and to use the natural evolution metaphor:

a) In a *Flexible Manufacturing System*, the parts family members are closely knit have a strong core of common features, and all variations are within the predefined boundaries. The concepts of Composite Parts, Master Plans and Variant/Retrieval Process Planning are both valid and useful. After a few generations, new product families gradually lose their roots (missing features) and develop new and different branches (additional features). The extent of difference between product generations depends on the number and nature of features changes.
b) In a *Changeable / Reconfigurable Manufacturing System,* and after many and different products generations, new product instances and different families / species emerge with much less resemblance to the original parent family and many of the familiar rules for process planning do not apply. The magnitude of change and distance between new and old members of the family significantly influences the characteristics of the process plans in this new setting.
c) The concept of *'Evolvable and Reconfigurable Process Plans'*, which are capable of responding efficiently to both subtle and major changes in '*Evolving Parts/Products Families*' and changeable and Reconfigurable manufacturing systems has, therefore, been introduced by H. ElMaraghy [33].

7.1 Reconfigurable Process Plans (RPP)

The process plans and planning functions are important links between the features of various generations of products / product families and the features, capabilities and configurations of manufacturing systems and its components throughout their respective life cycles. The efficient generation and reconfiguration of process plans is an important enabler for changeable and responsive manufacturing systems as it utilizes their new degrees of freedom.

Since the manufacturing resources and their functionalities are becoming reconfigurable, the products variations are increasing in scope and frequency and, the families of manufactured parts are also changeable and evolvable. Hence, H. ElMaraghy argues that the concept of *'Reconfigurable Process Plans'* (RPP) applies to both Macro and Micro level process plans.

New algorithms for re-planning and reconfiguring process plans should be developed to ensure the efficiency of this process. The reasoning to recognize the need for, trigger and achieve a reconfiguration of the process plan in response to both pre-planned and evolutionary changes in the product and/or manufacturing system must be established. The optimality (time, quality, cost, etc.) of the evolved and reconfigured process plans should also be verified and maintained.

7.2 Example – Family of Engine Cylinder Cover

A practical semi-generative process planning approach suitable for both reconfiguration of the products and manufacturing systems has been developed [9]. The macro-level process plan is formulated as a sequence of operations corresponding to a set of part features. Interactions between different part's features/operations are modelled using Features/Operations Precedence Graphs (FPG/OPG). The FPG/OPG graphs of a part family's composite part are modified to account for missing and added features. Optimal or near-optimal operation sequences that maintain the precedence relationships and constraints were obtained.

The developed method was applied to an industrial example of a single cylinder, air-cooled, overhead valve engine front cover family of parts defined by a composite cover and a corresponding master process plan.

A new Macro-level process plan for a new cover with different (new, missing and modified) features was generated and the manufacturing system machines had to be reconfigured accordingly. The cover (front & back), and features precedence graphs (FPG) for parts family composite and a new / reconfigured family member are shown in fig. 7.2 [9].

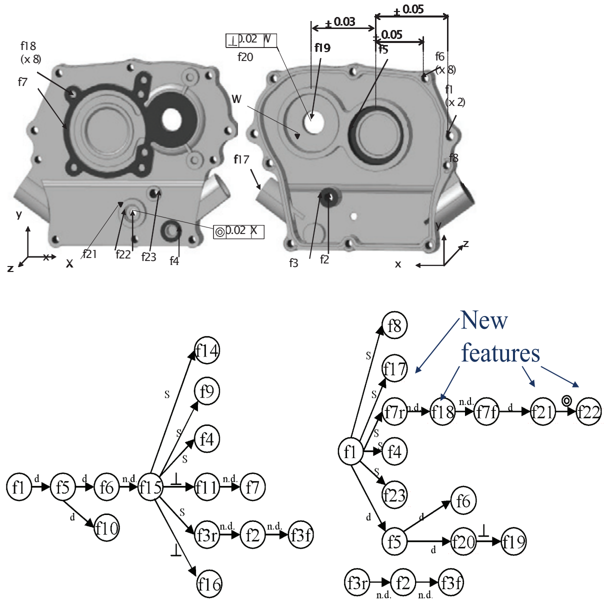


Figure 7.2: Composite cylinder cover.

It has been demonstrated that a hybrid system, which is variant in nature yet capable of generating process plans for parts with machining features beyond those present in the current part family's composite part best meets the current challenges.

7.3 Meeting the RPP Challenge

The designers of products, processes and manufacturing systems as well as production planners should be cognizant of the coupling between generations of products and manufacturing systems and capitalize on its potential benefits in improving the productivity of the whole enterprise. The automatic evolution of process plans is an important enabler of effective changeability. The evolution of manufacturing paradigms, the manufacturing system life cycle and evolution of products are intertwined. A new class of '*Evolving Parts / Products Families*' is proposed to capture this symbiotic relationship in contrast with the traditional notions of static parts families, composite parts and master process plans. The new concept of '*Reconfigurable Process Plans*' and the need to link their evolution and reconfiguration to the changes and evolution of both products and manufacturing systems are evident. A new innovative mathematical model and optimal solution algorithm for reconfiguring process plans were developed by Azab and ElMaraghy [8]. The key enablers for Reconfigurable process plans include cognitivability, evolvability adjustability granularity and automation ability as explained in chapter 2.

The new manufacturing paradigms and need for responsiveness and adaptability are highlighting the importance of developing new process planning approaches that can support the objectives of the new environment. Many research challenges, potential and exciting opportunities for improving manufacturing productivity and competitiveness lie ahead.

8 ADAPTIVE PRODUCTION PLANNING AND CONTROL

8.1 The PPC Framework

The Production Planning and Control (PPC) system is the central logistic control mechanism that matches the company's output and logistic performance with customer demands. Its general task is to allocate orders and resources over time, i.e. to plan, initiate and control the manufacturing of products [132]. Typical decisions are capacity adjustments (e.g. opening extra shifts, over times, subcontracting) or to trigger purchase orders. In addition, PPC has to monitor and, in case of unforeseen deviations, re-adjust the order progress or the production plans [134].

In this context, the term 'PPC system' encompasses the entirety of tasks, tools and people necessary to plan and control the logistic processes in a manufacturing company. The scope of application includes the three basic processes: 'Source', 'Make' and 'Deliver' [112]. Like production itself, the input and output stores of a company are covered by the PPC system [134], Fig. 8.1.

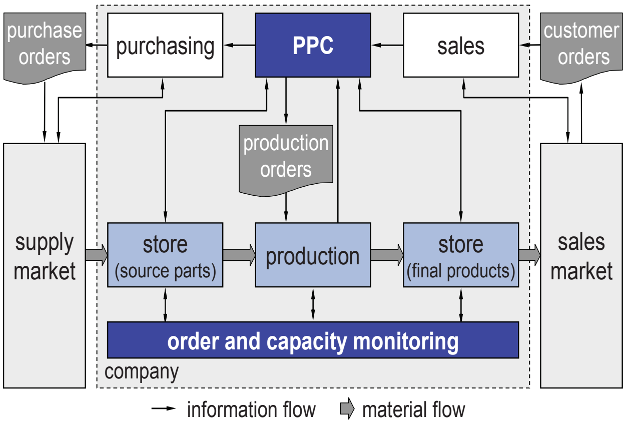


Figure 8.1: Scope of PPC (H-P Wiendahl).

The PPC system also cuts across company boundaries: It takes into account customer and supplier requirements since it follows Supply Chain Management principles. The management of the storage processes considers suppliers delivery performance as well as customers demand behavior. This chapter focuses on the changeability types: flexibility (level: segment / sub product) and transformability (level: site / product) (Fig. 2.5).

According to this understanding, the PPC software is part of the PPC system. The software tool, however, is used to plan and control the logistic process chain as well as to store the production master data and feedback data.

8.2 Design aspects of a PPC system

Complex systems cannot be captured as a whole, which makes it necessary to model them aspect-by-aspect. In socio-technical systems, activities are the central criteria that describe the system. Specker defines five perspectives for analyzing and designing IT systems [119]. Applied to PPC, six design aspects of a PPC system can be distinguished [130]:

- PPC *targets* require logistical positioning. If necessary, different targets need to be defined for different departments.
- PPC *functions* define the activities that are required to plan and control the logistic processes in stores and in production areas. PPC methods carry out the functions based on defined algorithms and data.
- PPC *objects* are the planning subjects of PPC. The most important are items (finished products, components or raw materials), resources (machinery, personnel, etc.), manufacturing processes and orders (e.g. customer orders, spare parts orders, etc.).
- PPC *processes* determine the logical sequence of planning and control activities. Thus, they define the workflow of order processing along the logistic process chain, i.e. the business process. The process steps related to the material flow follow the same logic but are not a direct subject matter of the PPC system: they are modeled as PPC objects.
- PPC *positions* determine the responsibility of the staff members. The classical PPC understanding assumes centralized decisions, hence, ignoring this aspect.
- Planning and control *tools* support the operational order processing by semi-automated PPC activities. This creates standards for operational activities. Staff, therefore, have more time available for the necessary planning and control decisions.

The first five design aspects constitute the logical core of any PPC system. The tools have to map the PPC design to the software effectively and efficiently.

8.3 Design matrix in PPC

To consider changeability the design aspects can be combined with the scope of change in a so-called design matrix, Fig. 8.2.

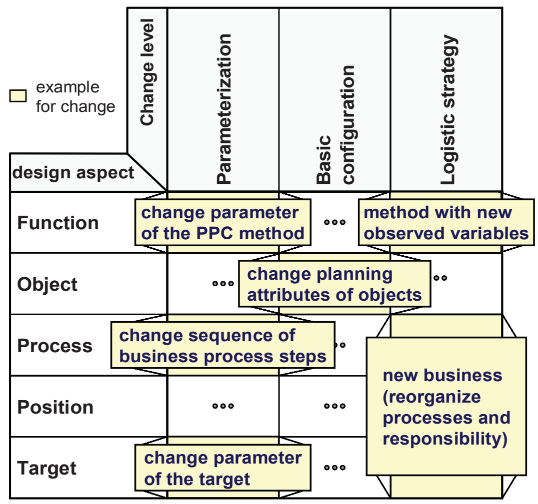


Figure 8.2: PPC design matrix (H-H Wiendahl).

Note that the matrix focuses on the logic core of PPC. It ignores the sixth design aspect 'PPC tools' because from user perspective a tool should only map the required design and changeability to software.

Three levels are relevant [129]:

1) *Parameterization*: The lowest changeability level in PPC is the adaptation of parameters. An example is adapting target values such as 'planned lead times'. This is the most common level of change, but it is hardly ever performed systematically.
2) *Basic Configuration*: At the second level, the basic configuration is changed with respect to the applied methods. An example is the change of the lot size rule from 'demand lot size' to 'Andlers Lot Size Formula' or 'Harris Order Quantity Model' [6] [51]. Most of today's PPC software includes this option. As a consequence, the PPC parameters on level 1 must also be changed.
3) *Logistic strategy*: The highest level of changes to PPC is the switch to another logistic strategy, usually along with a change of targets and their values. An example is the change from 'make-to-order' to 'make-to-stock' strategy. Consequently, new logistic targets are required, such as a change from 'schedule reliability' to

'avoidance of stock shortages'. Therefore, PPC methods (level 2) and the parameters (level 1) must be changed. In this case, at least the order generation rule must be turned from 'deterministic' to 'stochastic'.

The levels of change are linked as described. Changes at higher levels usually trigger changes at lower levels.

8.4 Changeability of PPC Tools

The PPC design matrix focuses on the core logic of PPC and neglects the sixth design aspect, 'PPC tools', which must also be changeable. In order to review IT tools with respect to changeability, their relevant elements must be known. First, the 'enablers of changeability' need to be defined, followed by the PPC elements that may change. Relating enablers to elements reveals the 'building blocks of changeability' in PPC.

Change elements of PPC

Apart from concepts and methods of IT technology, industrial experience showed eight change elements, which can be ordered into two categories (see also Fig. 8.3):

X building block for changeability

Design aspect	Change element \ Enabler	adjustability	neutrality	scalability	modularity	compatibility
Function	functional model	X			X	
	methods	X		X	X	X
Object	data model	X	X	X	X	X
	data interface			X		X
Process	process status	X	X	X	X	X
	process sequence	X	X			X
Position	user interface	X	X		X	
	authorization concept	X	X	X	X	X

Figure 8.3: Building blocks of PPC changeability (H-H Wiendahl).

- *Functional logic of order processing* is the logic of planning and control decisions; it is comprised of the PPC methods and their functional model, the data model as well as the data interfaces.
- *Workflow of order processing* refers to the structural and process organization. It is comprised of the desired process steps and their sequences, the authorization concept, as well as the user interface.

The changeability of these elements, in the PPC design phase, is facilitated by the enablers of PPC changeability including adjustability, neutrality, scalability, modularity and compatibility as explained in chapter 2. First application results identified these enablers as useful generic requirements when designing a PPC system.

Building blocks of PPC changeability

The combination of change elements with enablers of changeability allows two things: First, to rate the importance of a PPC enabler as well as a change element. Second, to find building blocks and describe attributes that support PPC changeability. This will be essential for analyzing and designing PPC changeability.

A building block is defined as the intelligent combination of an enabler and a change element. Fig. 8.3 displays these combinations and reveals the importance of the data model, the process status and the authorization concept.

It strikes the eye that the design function 'target' is not mentioned separately. Practical experiences show that changing targets go, in almost every case, with an essential change in the PPC system. This underlines the high influence of targets and their priority in general. Detailed analysis identified the functional model and its modeled relationships from targets to functions as main influence factors on changeability.

Industrial experience from PPC implementation projects underlines the high rating of these factors.

8.5 Changeable PPC Solutions

The paper neglects the topics organizational and human aspects (issues of change management and logistical knowledge see [71] [131]) as well as systematic deficiencies in PPC design [130] [133]. Therefore, the main deficiencies from a PPC perspective are functional models, planning and control methods as well as the data models and their interfaces.

Functional models

From a logical point of view, generic functional models support changeability. Lödding's 'model of manufacturing control' is one example: Its basic idea is to connect PPC functions with targets, as illustrated in fig. 8.4 [26]. Four basic functions are relevant and they are coupled with the targets through manipulated and observed variables. The model easily and consistently supports a basic PPC design of the aspects 'function' and 'target'.

Planning and control methods

To speed up implementation or to lower the threshold for changing PPC methods [51] [62], experts emphasize the influence of PPC methods on changeability. Two different approaches can be used:

- *Generic methods*: The first approach is to develop methods able to build different methods only by adapting parameters. Examples are load-oriented order release (BOA) and cumulated production figures (CPF): Lödding extends both to generic methods, BOA for order release and CPF for order generation [75].
- *Flexible methods*: The second approach is to develop methods capable of dealing with various PPC requirements. Agent-based systems are an emerging technology. Their common properties (e.g. autonomy, intelligence, ability to interact) enable them to act in changing environments and their decentralized decisions enable the desired adaptability in accordance with the actual situation [84]. Three PPC application domains for multi-agent systems (MAS) have been suggested [84]: production planning and resource allocation, production scheduling and control as well as an integrated scheduling and process planning.

It should be noted that the criteria changeability and adequate functionality of a method are sometimes mixed up: The first criterion describes the ability to adapt a method to different requirements and refers to the re-design phase. In contrast, the question of adequate functionality refers to the operation phase and describes how an algorithm fits to specific logistical requirements. Experience shows, that superior methods follow the closed-loop principle (see chapter 9) and are typically more sophisticated which guarantees a better logistical performance. But this obstructs changeability. Therefore, changeable methods do not necessarily have a superior functionality.

Data models

Data models influence changeability from a more IT-driven point of view. Two fundamental different approaches are:

- *Hierarchical models*: In this approach, the predetermined structure supports consistent and complete data. As a result, the user should not face problems with different results based on different data requests because hierarchical models have – per definition – rigid boundaries for control and information sharing.

- *Non-hierarchical models:* This approach creates options to enable more flexibility. As a result the user should be able to adapt data models and the implemented information quickly but possibly jeopardizing data consistency and completeness.

The comparison of current ERP software illustrates the differences between these approaches: Some suppliers provide an integrated solution with a hierarchical data structure. Its main advantage, consistent data, leads to the often-criticized loss of flexibility under changing circumstances. Other suppliers provide data models for each site (non-hierarchical) with more flexibility concerning changing requirements (e.g. integration of new business units). However, data redundancy creates problems with data integration and consistency.

Data interfaces

A complementary approach for achieving changeability in IT with relevance for PPC is to standardize data interfaces. It assumes local data models with a low necessity to change information and follows closely the black box idea. In practice, two different solution ideas can be found:

Complete approaches of supporting data interchange by describing each case very detailed, resulting in a high implementation effort. One example is EDIFACT, the most common standard in various industrial sectors containing 550 elements within 100 segments.

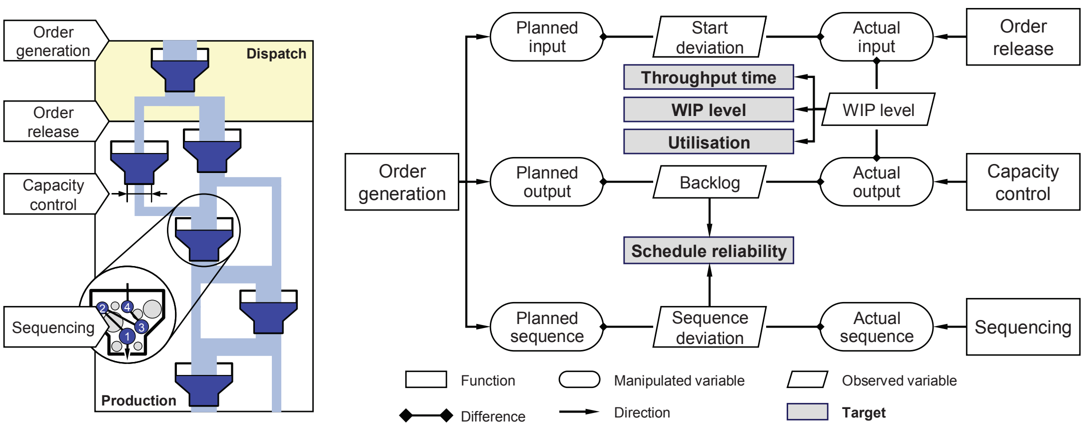
Selective approaches of supporting data interchange by focusing on relevant cases. This enables "lean" solutions with low implementation effort. For example, the OpenFactory standard is limited to 20 messages and 185 elements [82].

The underlying question is whether it is possible to perform 80% of the transactions with only 20% effort, while avoiding the numerous special cases in practice?

8.6 Further research

This chapter described changeability from the perspective of production planning and control. The focus was on technical aspects, and organizational and human aspects that also are relevant to achieve changeability were neglected.

Bearing this in mind, further research should concentrate on three aspects: First, further development of functional models to obtain a generic structure. In production control, initial results are available [75], but a corresponding model for planning is still missing. Second, development of a structure of basic PPC parameters, ideally arranged according to the functional models. Third, development of methods that are adaptable and scalable. These have to be robust with respect to demands concerning functional logic and complexity. These technical results would structure PPC more generically and also would support organizational and human aspects of adaptive PPC.



a) Functions b) Interrelationships

Figure 8.4: Model of manufacturing control (extended version of H. Lödding).

9 ECONOMIC EVALUATION OF CHANGEABILITY

9.1 Importance of economic evaluation

Although in general changeability is considered highly relevant in industry, the changeable construction of a workstation, a manufacturing system or a whole factory site is often not considered. The main reason is that changeability often requires additional investment, which can usually be accurately estimated but economically not justified with the same accuracy [147].

The benefits of changeability, per definition, are usually felt in the long term. Tolio sees two main benefits of changeable production systems; first it enables economies of scope. A changeable system allows the contemporary production of different products whose volumes, taken separately, would not justify the adoption of a specific production system but together they can justify the adoption of a single system capable of producing all of them.

The other benefit is the reduction of costs for required change processes [80] [79]. The reduction of these costs during the life cycle of the system depends on the number and extent of necessary changes in the future.

As these prognoses are highly uncertain and therefore the benefits of changeability can not be “proven” for the near future, decision makers tend to focus on seemingly low cost investments [108]. Although the cost of changing over the life cycle can sum up to about 50% of the initial investment (e.g. in automotive body shops) they, therefore, invest in less changeable alternatives [110]. In addition, publicly traded companies are often judged on quarterly results; hence, often management prefers minimizing of investments without consideration of later side effects. Other enterprises tend to invest in extensive changeability features for strategic or safety reasons, without fully utilizing this capacity.

Hence, the need for a monetary evaluation of investments in changeability is valid for all types of changeability alike, but the uncertainty grows with the length of the period to be considered and the value of the additional investment. For example the higher investment for a factory building can be amortized over a longer period of time than a reconfigurable manufacturing system. Separate but comparable approaches for the economic evaluation of changeability have been developed for the different types of changeability (see among others [40] [113] [108] [53] [96] [139] [122] [106] [41] [143] [28])

The basic concept of most of these approaches is to analyze possible future scenarios and their probability of realization, define in each of those scenarios the benefits that changeability provides and compare them with the cost of changeability.

9.2 Life cycle costing of an RMS

Denkena and Drabow presented a method for evaluating the changeability of a manufacturing system, with a special focus on modularity, which integrates the economical aspects of changeability as one of the relevant criteria in a benefit analysis [24] [25]. The importance of differences in the initial investment compared to differences in the changeability measures of system alternatives can be captured using weighting factors to consider the relevant environment for the manufacturing system, e.g. whether the manufacturing system is located in growth or a stable segment.

Another approach in research on the level of reconfigurability is the life-cycle-cost-approach for a manufacturing system. It not only considers the initial investment but also other relevant costs during the entire life cycle. This approach considers the hidden costs of conventional manufacturing systems that occur when a product changes or a higher capacity is required [124].

Schuh et al. developed a methodology for flexibility evaluation for an automotive body shop within the project Lifecycle Design for Global Collaborative Production (LicoPro). This helps evaluate the life cycle costs of several models. First it enables the planner to gather information from the markets, e.g. different scenarios with associated probabilities of occurrence. Then production system alternatives are configured and modelled. Finally the alternatives are evaluated by a simulation approach, in which each alternative and each scenario is first treated separately in order to gather the occurring costs in this specific case. Finally the simulation results are aggregated and presented among others in the “flexibility window” (fig. 9.1). The authors explain is as follows [110].

“Each key performance is represented by one dimension in the Flexibility Window: the x axis shows the delivery rate, the y axis indicates part costs.

The performance of a production system is indicated by its position in the diagram. An optimal production system, as indicated by the point in the lower right corner of fig. 9.1, would achieve a delivery rate of 100 % at minimal costs (k_{min}). However, a real system will perform worse and cost more. Hence, it will be somewhere above and left from the ideal system in fig.9.1. An example is indicated by the cross.

If not only one market scenario is considered but instead a multitude of scenarios as compiled in the strategy module, one looks at a range of delivery performance rates and at a range of part costs. When these two ranges along the x and y axes, respectively, are combined, a rectangle results which the authors named Flexibility Window. Note that the least probable 10 % of each range are left out in order to disregards outliers, i. e. very improbable cases.

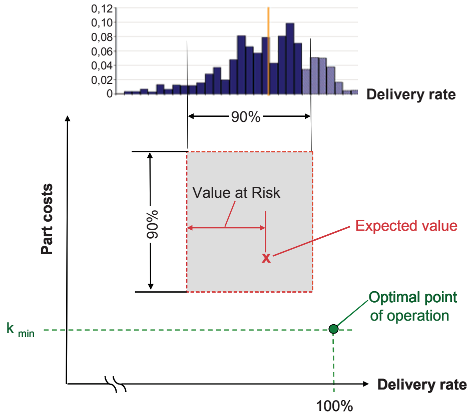


Figure 9.1: Flexibility window [110].

The dimensions of the Flexibility Window along the axes indicate the risk of the system: the wider the rectangle, the unsure the performance of the system. Target is hence a small rectangle as far to the right and as low as possible”.

9.3 Economic evaluation of transformable factories

For transformable factories several approaches can be described and they all have to consider a high degree of uncertainty and complexity.

Break-even analysis

A simple evaluation of the investment in changeability can be done with a break-even analysis. The initial investment for different alternatives with different changeability is calculated. In addition, for each system the necessary cost for a defined change is estimated. Then a break-even analysis, as shown in fig. 9.2 for the example of different media distribution systems, is performed [94] [139] to determine, for a given degree of necessary change during the life cycle of a certain factory, whether the additional investment in changeability is justified.

A classical and modular grid pipe installation system is compared (fig. 9.2). The initial investment for the classical and grid systems is 133 T€ and 138 T€ respectively.

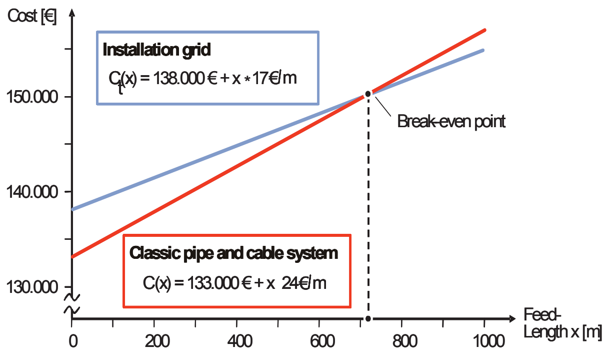


Figure 9.2: Comparison of classical and modular grid pipe installation system [94].

The cost of installing or de-installing of one meter of pipe is 24 and 17 €/m respectively. As a result one can see that for more than 714 m of additional or changed feed line the modular grid is economically superior to the classical system in addition to other advantages like shorter installation time and less disturbances.

This method ignores the time value of money but is on the other hand easy to use for practitioners.

NPV and real options

In general long-term investments should be evaluated economically by means of a discounted cash flow method. The net present value calculation is most commonly used, either with or without the integration of uncertainty using assumptions about the future expected cash flows.

Heger developed a twelve-step evaluation method of transformability for factory objects based on the evaluation of the transformability of a factory described in chapter 5. The initial investment and the expected costs and frequency of change processes over the life cycle are aggregated into an expected net present value for factory objects with differing changeability such as the expected frequency and costs of change processes such as an extension of a building and the integration of new gates. Besides this economic measure, the actual and the target transformability of a factory are calculated, which allows an integrated decision-making. [53]

Another important approach is to regard investments in changeability as real options (see among others [10] [147] [149] [150] [1] [5]). Options in financial theory include the right, but not the obligation to buy or sell a specific asset at a predetermined price at a pre-set date or during a limited pre-set period of time.

In analogy, changeable manufacturing systems would have the right, but not the obligation to modify the system's structure when new information is available. The exercise price is the additional investment required for the change process and the exercise date may span the whole lifecycle of the system. The price of the option is the additional initial investment for the changeable system compared to the traditional system.

Zäh et al. have integrated this real option approach into a methodology, which allows creating and evaluating production system alternatives with different degrees of changeability. In this methodology (fig. 9.3) the most important uncertainties are modelled in a decision tree, which describes the different states of a system. The branches of the tree are then used as an input for the Monte Carlo-simulation of the effects of other uncertainties in the environment. Consequently the simulation results lead to information about investments, cost distributions etc. that can be integrated into an expected net present value distribution for each alternative, which can be used as a basis for making decision [147].

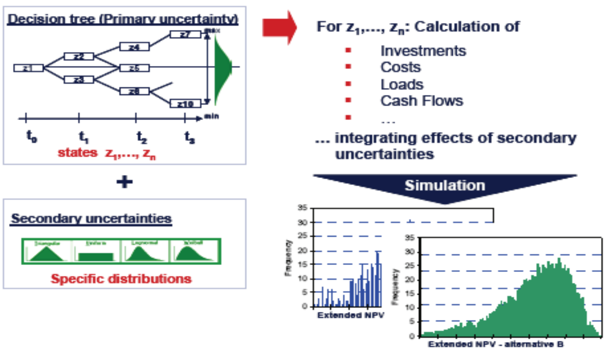


Figure 9.3: Monetary evaluation of investment alternatives using the real option approach [145].

9.4 Limitations of the economic evaluation

Tolio comments that changeability has a strategic value that normally cannot be evaluated only in economical terms. Sometimes even future scenarios cannot be formalized precisely. Still there may be a perceived need in the company that changeability will be necessary. In this situation tangible and intangible benefits must be considered when deciding the right level of changeability. El-Maraghy and Kuzgunkaya [34] developed a fuzzy multi-objective decision support tool, which considers both lifecycle costs and intangible benefits such as system responsiveness and complexity, for the planning and justification of RMS configurations over the whole life cycle. Their results have demonstrated the advantages of incorporating intangible benefits in the lifecycle evaluation of RMSs and changeable manufacturing systems. It is, therefore, necessary to have evaluation techniques that allow defining the level of changeability, which is consistent with the perception of the managers and the experts in the field. Multi-attribute evaluation techniques can be used for this purpose [83] [78] [5].

In general, all the discussed methods can only support the final decision of the management. The main advantage is that planners are encouraged to think about the necessity of changeability and to consider it wherever possible. Since practically all suppliers of factory equipment have to constantly think about adaptability of their products to customers needs most of them utilize modular designs, which makes changeability much cheaper than in previous years.

10 THE CONTROL LOOP OF CHANGEABILITY

10.1 Changeability cycle

The purpose of future factory design activities should not be to achieve the transformability of objects at any cost. Quite the contrary: having defined the levels, objects and enablers of changeability, the question arises as to which degree of changeability is *appropriate* in a given situation.

It must be stated first that it is not possible to define an absolute changeability. One can imagine cases of extreme changeability: e.g. a circus, the equipment of which is completely disassembled in a few days, travels to another place and is reassembled again in days; or a theater in which a play is on stage every night, changing scenery within minutes.

Changeability can be interpreted in analogy to quality. Quality in a broad sense is defined as "conformance to requirement" and is the sum of multiple separate attributes. For changeability, this means that a company has to define the changeability requirement, compare it with the actual conformance and aim for continuous adaptation. Fig. 10.1 shows the resulting cycles for action.

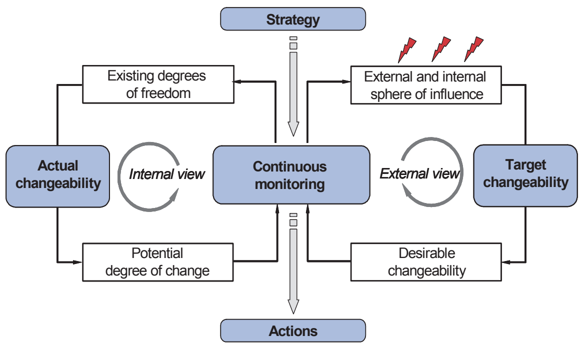


Figure 10.1: Adaption cycle of changeability (H-P Wiendahl).

Triggered by external and internal impacts (see fig. 1.1) the *target changeability* has to be set. This refers to the scope (operational, tactical, and strategic), the level (factory, segment, cell, and workplace) and the object (product, process, volume, mix).

The result is the *desirable changeability*. On the other hand the existing production has certain degrees of freedom to change, hence the actual changeability offers a potential for changeability. Typically the potential is not large enough to cope with the desired changeability. Therefore, an economic evaluation has to be performed. Finally the management has to decide upon the overall corporate strategy and actions to be taken.

The dynamic implications of closed-loop structures in production have been studied since 1952 or earlier [118]. The applications have ranged from understanding the dynamic behaviour of workstations and groups of workstations [102] [137] [64] [29] [123] [23] [105] [12] to the dynamic behaviour of supply chains [56] [27] [60] [43]. The process of change, and its dynamics, can be viewed as having both closed-loop and open-loop components. Fig. 10.2 shows that change at each of the production levels shown in fig. 10.3 can be viewed as being the result of two types of decisions:

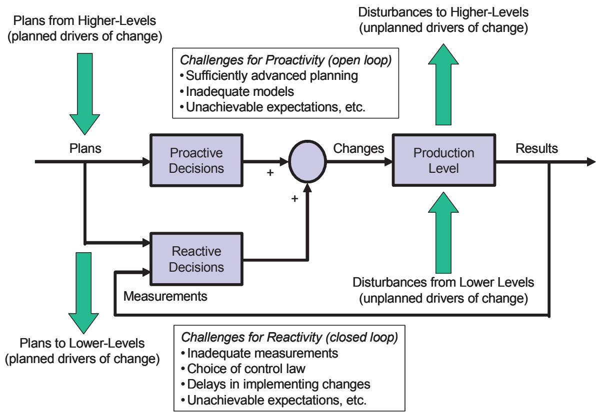


Figure 10.2 Generic control structure of change (Duffie).

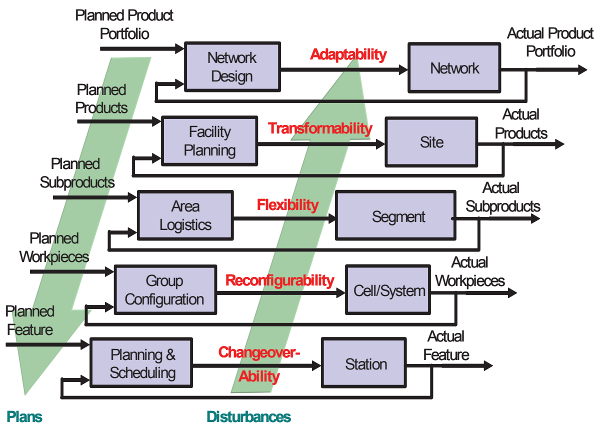


Figure 10.3 Changes at the Various Production Levels (Duffie).

Proactive (Open-Loop) Decisions – these decisions are based on reliable models that predict the changes that need to be made at the given production level to achieve planned results; and

Reactive (Closed-Loop) Decisions – these decisions can be made in the absence of a reliable model and are based on measurement of the actual results and using a control law to make continual incremental changes that tend to remove differences between planned and actual results over time.

Proactive approaches usually achieve results quickly, but accuracy is limited by the fidelity of the models used. Reactive approaches, on the other hand, first require detection that planned results are not being achieved. Changes then can be made, and actual results are expected to converge over time to those required; therefore, reactive approaches usually achieve results slowly, but planned results can be achieved in the absence of a high-fidelity model.

Plans generally are established at the higher production levels and are applied at and drive change at lower levels; for example, the portfolio of products at the production network level results in product plans at the facility level. Conversely, disturbances are unpredictable, difficult-to-model factors that must be reacted to. They can be considered to be unplanned drivers of change, and they generally occur at the lower production levels shown in fig. 10.3 and propagate to higher levels.

For example, the production network level may need to react to fluctuations in currency exchange rates at the facility level. Deif and ElMaraghy [23] proposed a closed-loop controller at the tactical level for an agile dynamic Manufacturing Planning and control (MPC) and inventory systems to respond to fluctuations in market demands.

Table 9.1 gives examples of the types of plans, proactive decisions, reactive decisions, and disturbances found at each level together with an indication of the timeframe in which response to change might be expected.

To achieve changeability at all levels, it is necessary to understand the drivers and mechanisms of change and the extent to which decisions can made proactively as opposed to reactively, thereby creating opportunities to accelerate the pace of change.

Production Level	**Plans**	**Proactive Decisions**	**Reactive Decisions**	**Typical Change and Timeframe**	**Typical Disturbances Affecting this Level**
Production Network	Product Portfolio	Network Design	Network Restructuring	• Global Location • Shipping • Communication, etc. Months-Years	• Market Trends • New Products • Labor Cost • Exchange Rates, etc.
Site	Product	Facility Advanced Planning	Facility Adaptation	• New Facilities • Facility Closure • New Lines, etc. Weeks-Months	• Product Mix • Produce Design, etc.
Segment	Sub product	Planned Area Logistics	Area Logistics Adaption	• Line Design • Process Selection, etc. Days-Weeks	• Market Demand • Component Mix • Component Design etc.
Cell/System	Workpiece	Planned Group Configur-ation	Adapt Group Equipment & Logistics	• Backlog • Inventory • Workpiece Design, etc. Hours-Days	• Capacity • Process Plans • Machine Configuration • Training, etc.
Station	Feature	Planning & Scheduling	Shop-Floor Decisions	• Setups • Job Sequence • Process Para-meters, etc. Minutes-Hours	• Rush Orders • Equipment Failures • Material Shortages • Personnel, etc.

Table 10.1 Change attributes of production levels.

There is a need at all levels of changeability to improve the models used for making proactive decisions and improve the control laws and measurement methods used for making reactive decisions, with the goal of making production networks and their components fast-acting and robust in turbulent environments.

The change cycles aims for a continuous adaption between the market needs and the actual performance of the production during the whole life cycle of a factory. Fig. 10.4 serves as a map of changeability. It illustrates the factory life cycle phases in the upper part starting with the design or redesign of the factory followed by the realization and start up until the first change becomes necessary.

10.2 Changeability process

Changeability can be seen as a process with two phases as shown in fig. 10.4 lower part.

In the design and implementation phase, the necessary adaption of the transformation objects has to be determined followed by the transformation to the new level of changeability. The factory organization is now technically empowered to change the identified objects on the desired level. At the right moment, either a reactive or proactive change is performed. This process is similar to a factory set up when facing a new production situation.

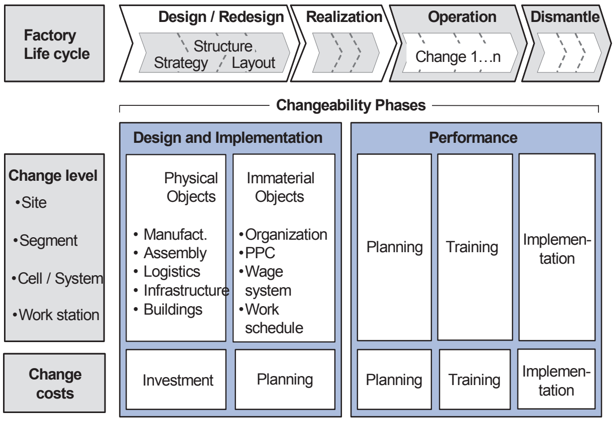


Figure 10.4 Map of factory changeability (H-P Wiendahl).

The performance of the change itself also has typical phases. First, a work plan is developed that describes the sequence of operations and their duration. Second, the people involved in the change have to be trained. And third, the changeover itself has to be implemented using the previously built-in changeability attributes. The procedure can be compared with a pit stop for a race car in which a change of 4 wheels is required. There is a precise plan that specifies which person has to do what with which tools and in which sequence. Then the team is trained by doing it over and over again, improving the process step by step. Finally the real situation occurs and within 12 seconds the wheels are changed.

But even highly transformable objects do not adapt to changes of the environment by themselves. It needs always a human input to trigger and perform the transformation process. Therefore, other requirements for a successful transformation process must be identified besides the technical transformability of the objects. These are connected with the human being itself in terms of change competency (e.g. motivation or education), leadership (e.g. giving permission and resources) as well as culture and are discussed under the term of change management [93] [44] [45]. In addition, Reinhart sees intelligence and creativity as other important factors besides the ability to react [104].

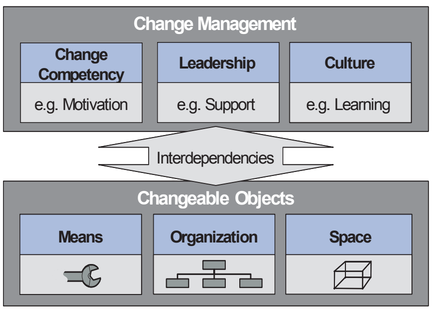


Figure 10.5: Prerequisites for a successful change.

These factors have been extensively discussed in the field of change and innovation management but are rarely connected with the transformability of a factory and their objects, although this connection offers significant synergies. Fig. 10.5 illustrates that the interdependencies have to be considered in order to support the necessary change processes within the factory by adequate objects as well as create the environment to be able to fully use the potential of the transformability of the objects.

11 CONCLUSIONS

Flexibility of manufacturing systems has been treated as an important topic for their design and operation for many years. With the increasing global interdependencies of manufacturing firms and market dynamics, the whole factory including assembly, logistics and even the site and buildings have to be considered as well. This calls for a more comprehensive view of not only the different levels and objects of a factory but also the scope and level of flexibility.

The paper proposes the term “Changeability” as an umbrella for the different types of flexibilty at various levels and objects of a factory. To date, the measures of changeability as an attribute are not well defined. However, its definitions, metrics and interpretation, similar to quality, are of great importance to the ability of manufacturers to compete effectively. The outlined issues and examples serve to illustrate the importance of changeability as an enabler for agility and flexibility and its potential role in today’s manufacturing and economic environments. Further research should, therefore, answer several open questions:

- What are appropriate models to describe and measure changeability at the different levels of the manufacturing enterprise?
- Is it possible to define generic changeability enablers for the different levels and objects within a factory?
- What new models and methodologies are required such that process planning can capitalize on the new degrees of freedom offered by changeable manufacturing?
- Which production planning and control methods are suitable for changeable manufacturing systems?
- How can the change process itself be planned and performed with an appropriate speed and effort?
- How can quality be managed within frequently changing manufacturing facilities and global supply chains?
- What is the impact of changeability on the feasibility and economic investment justification?
- What is the impact on human skills and involvement in changeable factories?
- What are the social standards, which ensure that in globally distributed and changeable production enterprises and networks employees’ work under acceptable conditions?

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