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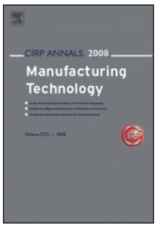

SPECIES – Co-evolution of Products, Processes and Production Systems

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Abstract: Manufacturing enterprises are changing the way they behave in the market to face the increasing complexity of the economic, socio-political and technological dynamics. Manufacturing products, processes and production systems result in being challenged by evolving external drivers, including the introduction of new regulations new materials, technologies, services and communications, the pressure on costs and sustainability. The Co-evolution Paradigm synthesizes the recent scientific and technical approaches proposed by academic and industrial communities dealing with methodologies and tools to support the coordinated evolution (*co-evolution*) of products, processes and production systems. This paper aims at reviewing and systemising the research carried out in the field of manufacturing co-evolution with a particular focus on production systems. An introductory investigation of various industrial perspectives on the problem of co-evolution is presented, followed by the description of the Co-evolution model and the methodology adopted for framing the existing scientific contributions in the proposed model. Then, the core part of the work is presented, consisting in a systemized analysis of the current methodologies dealing with co-evolving product, process and system and a description of problems that remain unsolved, thus motivating future research strategies and roadmaps.

Keywords: Product-Process-System, Co-evolution , Factory of the Future.

1. Introduction and problem statement

Manufacturing is radically challenged worldwide by complex economic, socio-political and technological dynamics that have a tremendous impact on enterprise behaviour in the market, and consequently, on the research priorities of the scientific community. Many external drivers are modifying the way products are designed and exploited, among them the introduction of new materials, technologies, services and communications, the pressure on costs and the attention paid to sustainability specifications. For example, the advent of composites in the aerospace and automotive industries has required the design of more complex product shapes and the achievement of challenging performance levels. The introduction of new legislation in manufacturing to reduce the product environmental footprint has had a profound influence on manufacturing processes and has resulted in the birth of a new generation of production equipment characterised by higher energy efficiency, for example machine tools [1, 2]. Furthermore, the need to increase company competitiveness is leading to conceive products as more complex entities, with the physical product enriched by service and communication activities.

These aforesaid developments have led to requirements such as responsiveness and flexibility in production that are being transformed into cognitive adaptability [3], changeability [4], self-diagnosis, self-resilience [5], self-improving environment paradigms and co-creation [6]. Companies are continuously absorbing these change drivers by shaping their corporate strategy and by combining external needs to the internal requirements of efficiency, productivity and cost-effectiveness. The inherently complex dynamics of change propagation has impacted all levels of the organisation, as illustrated in Fig. 1.

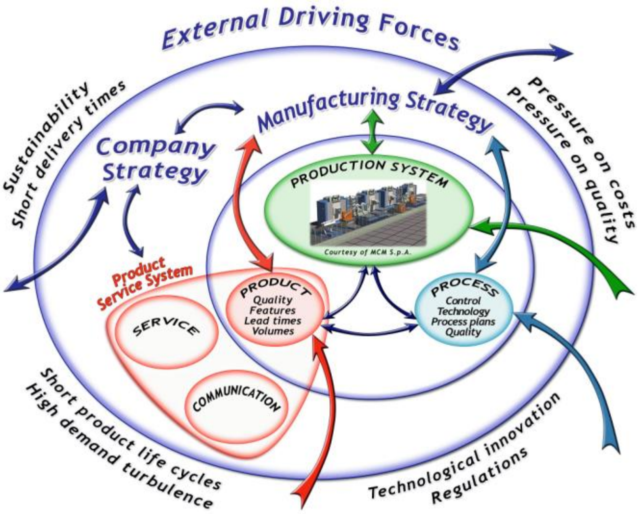


Fig. 1. Manufacturing dynamics.

Figure 1 illustrates the integration of products (as part of a product service system, i.e. physical product, service and communication), processes and production systems and their connection and reciprocal influences with the strategic decisions of the company as well as with the market (e.g. external driving forces). Herein, the change propagation behaves as a cause-effect wave across the enterprise, spanning the domain comprised between the corporate strategy and the physical plant. So that, referring to the example on the introduction of new environmental regulations, it can be noticed that the reduction of factory emissions severely impacts on the adopted processes and resources, constraining the design of machine tools in their requirements for higher thermal stability without the use of complex cooling systems, requiring materials with higher stiffness and damping, hydraulics and spindles configured for reduced energy consumption, and components configured for re-use or re-manufacture after their end of life.

Thus, the generation and propagation of changes create a multitude of possible scenarios that companies must face in order to stay competitive. The scenarios are often unpredictable and this represents a major cause of complexity when operating in dynamic manufacturing environments together with a lack of unified solution approaches. The term "co-evolution" is an illustration of such a challenge. It represents the ability to manage strategically and operationally the propagation of engineering changes to gain competitive advantage from the resulting market and regulatory dynamics. The issue of "*co-evolution*" and its complexities have been a significant interest to the scientific and industrial communities and resulted in the creation of an international working group in 2006, titled *SPECIES - robuSt Product$_i$on system Evolution Considering Integrated Evolution Scenarios*, within CIRP (The International Academy for Production Engineering). The primary objective of this working group was to investigate the different aspects related with the co-evolution of products, processes and production systems [7].

This paper provides an overview of the co-evolution of products, processes and production systems by introducing a modelling framework, as well as current research and practices. It also identifies key open research and practical issues that need to be addressed by the research community.

1.1. Industrial motivation

A company's ability to manage co-evolution of product, processes and production systems is strictly related to the company's success in the market. The way companies perform is determined by drivers such as market segment and demands, product variety, price elasticity and the role the company plays in the supply chain [8].

More and more industrial companies that continuously face challenges related to the co-evolution of products, processes and production systems have already envisaged and developed customised solutions to help in tackling the problem. The following subsections present several industrial cases in which new approaches to cope with the co-evolution problem have been adopted. Three groups of industrial cases have been identified according to the role played by the companies; these include industrial equipment users (Sect. 1.2.1), industrial equipment producers (Sect. 1.2.2) and providers of Digital Enterprise Technologies (Sect. 1.2.3). These cases have been selected based on their ability to:

- address different concepts and needs for co-evolution;
- analyse different sectors and industries (e.g. automotive, aerospace, equipment production, component manufacturing);
- embrace different cultures and countries (e.g. Italy, Germany, France, UK, Japan, and USA).

The industrial cases support the following premises:

- The co-evolution of products, processes and production systems is a relevant industrial challenge, the complexity of which will continue to grow in the future.
- The co-evolution challenge can be addressed on multi-levels specific to the industry and markets (e.g. flexibility, reconfigurability, modularity, technology migration);
- Managing co-evolution is economically beneficial both for technology users and for providers. Industrial companies are experiencing a trend towards increased investments in their ability to drive co-evolution.

1.1.1. Industrial Equipment Users

The family of industrial equipment users is represented by a multitude of companies with different profiles; however, they all combine information of product, process and physical resources in their plant. Generally, industrial equipment users embrace the co-evolution problem better than other industries , because in order to deliver finished and/or semi-finished products to their final customers they have to use processes implemented by production systems.

With reference to the examples presented below, the strategic decisions adopted by companies to manage the co-evolution problem will consider the following key points:

- the problem of determining the system configuration which better fits the production requirement over time;
- the problem of accommodating production changes by designing reconfigurable machines and auxiliary equipment, and adjusting the production plan and schedule.

The first aspect has been considered with reference to a large Italian company that operates in the automotive sector, as a supplier of semi-finished engine blocks for various automotive companies. A recent evolution in demand has led the company to supply finished or nearly-finished engine blocks rather than performing only roughing operations. The need for additional machining operations required the introduction of an enhanced *system reconfiguration* to enable the execution of a wider and more complex set of machining operations. The original system configuration consisted of a rigid transfer line, following the common practice of associating stable and foreseeable demand of products with rigid production system architectures. The existing architecture was reconfigured into a hybrid flexible manufacturing transfer line composed of a set of flexible cells organised as flow lines and connected by flexible material handling devices. Each cell consists of 5-axis CNC machining centres which guarantee the machining accuracy/repeatability required by the product types. Despite each cell of the line being assigned to a specific process step, the presence of very flexible machining centres guarantees the robustness to handle product and process volatility and changes in part routing.

The second example involves RCM S.p.A., an Italian Small Medium Enterprise (SME) acting as subcontractor of mechanical components for the automotive and motorcycle markets. Its production system consists of 19 different manufacturing cells, and the production planning has to manage more than 100 part types for several customers. As the machining centres have different characteristics (e.g. spindle speed, taper type, pallet table and work cube) and different process times for the same workpiece, each machining centre is qualified to process a certain set of operations only; this policy allows RCM to reduce the necessary number of fixtures and tools. Nevertheless, critical operation types are assigned to more than one manufacturing cell; the objective is to increase the system robustness in facing urgent and unforeseen orders. The strategy of classifying the operations on the basis of their criticality allows RCM to focus the ability to be responsive on *continuous production planning and scheduling*.

The last industrial example involves Wilhelm Karmann GmbH, a producer of body-in-white components in the automotive sector. As the company business is focused on ‘niche cars’, there is a strong need for customization and, at the same time, the wide variety of product versions and models demand high levels of production system flexibility. This particular environment led Karmann to develop the concept of Migration Manufacturing [9] wherein different body work models and their variants are manufactured on a single production line with a complex architecture. However, the layout can be modified thanks to the *resource modularity* and frequent changes can be accomplished by the use of *modular auxiliary devices*, which migrate across the plant along a specific “migration path”. The concept of modularity has been exploited by this company in order to enable the movement of the manufacturing workstation across the plant, when production requirement changes occur.

1.1.2. Industrial Equipment Producers

The role of equipment producers is to provide users with the resources to manage the co-evolution problem, often basing the system solutions on partial information about the products. The strategies of equipment producers in facing the co-evolution problem mainly involve:

- the development of a strategic market analysis to identify the hardware and software solutions that are able to accommodate new products and production technologies, often providing the customer with additional services;
- the implementation of flexibility and reconfigurability paradigms at the system as well as production equipment levels, such as machine tools and assembly equipment;
- the design of modular devices to enable production equipment reconfiguration.

The first industrial case involves MCM S.p.A., an Italian machine tool builder that specializes in designing and manufacturing machining centres, flexible production systems and ad-hoc solutions for specific applications. MCM recently coordinated an intensive market investigation to develop a *strategy* aimed at enlarging its market share. A first outcome of the analysis regarded the company portfolio: MCM, traditionally playing in the automotive sector, anticipated the opportunities offered by the aerospace sector by designing new machine tool models with special work space and spindle power to enable machining titanium parts. A further outcome was the introduction of a *focused flexibility paradigm at the system level* by identifying production system solutions tailored on present and future production requirements. The proposed solutions were designed to support process flexibility, since the part program is treated as a network of operations that can be assigned separately to more than one machine [10]: this allows handling alternative operations or alternative sequences to manufacture the same part type, thus providing degrees of freedom when balancing the machine loads in the plant. By also focusing flexibility on future requirements, MCM contributes in limiting reconfiguration and ramp-up times that represent typical problems in dynamic environments [11, 12, 13]. In addition, MCM elaborated a more complex concept of product, consisting of the physical product and associated service, by providing the customer with a software platform, called jFMX, for the production management and for the control of physical devices of the system. Thus, when product and process changes occur, jFMX can support the customer to continuously adjust the scheduling and process planning.

Industrial solutions in the direction of *production system modularisation and reconfigurability* have been also proposed by Xenon Automatisierungstechnik GmbH, a small German company that produces special purpose machines, automatic assembly lines and packaging machines, mainly for automotive and electronic devices. This company recently worked on the concept of Extensible Hybrid Assembly Systems that consists of small autonomous modules of assembly systems which can be easily composed to form production lines. The assembly systems are hybrid as the automated workstations can be integrated with manual workstations autonomous modules The main idea is that when the customer needs to face evolving production requirements, a first reasonable decision could be to assign to the manual workstations those operations which are more complex to automate and therefore, would require a higher investment. However, the system’s modularity facilitates easy substitution of the manual workstations with automated one, in case the demand becomes more stable or less difficult to forecast. An example of this transition is shown in Fig. 2.

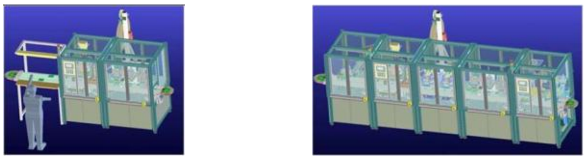

(a) (b)

Fig. 2. Examples of modular assembly systems with (a) semi-automated and (b) automated configuration (courtesy of Xenon).

The concepts of *modularity at system and machine levels* have also been exploited by Mori Seiki Co. Ltd., one of the largest Japanese manufacturers of machine tools. This company produces small size, modular machine tools that can be easily integrated in a production line for quick modification of its production capability through reconfiguration. As shown in Fig. 3, by changing production modules the production system can evolve and respond to new technological product requirements as well as new production volumes. Reduced machine size has a positive impact on the performance at the system level because it allows designing compact system layouts, which lead to shorter system flow times, fewer load/unload operations and less floor space requirements [14].

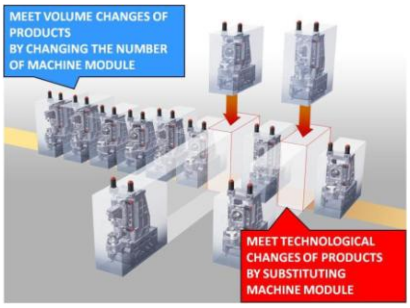
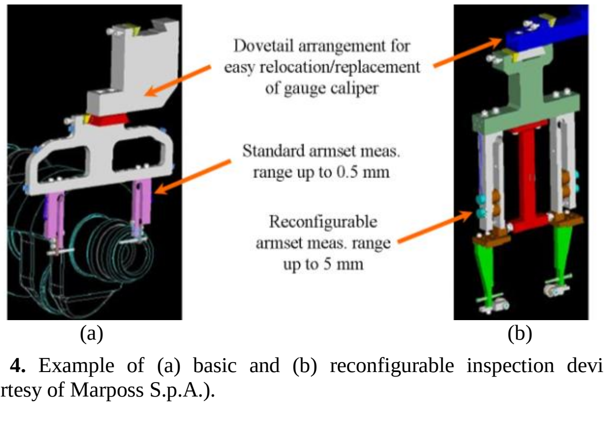


Fig. 3. Examples of reconfigurable system solution composed of small size machine tools (courtesy of Mori Seiki).

In the field of *modular and reconfigurable machining centres*, MAG Industrial Automation Systems, an international leader in the capital equipment market, has begun producing reconfigurable solutions for many applications (e.g. general machining, job shop, die and mould, aerospace, medical sector, etc.). For instance, a series of horizontal machining centres is designed with five basic configurations that can be customised with more than 100 options. The customer can design a machine by choosing among two pallet dimensions, various tool interfaces, six spindle options, four control options and three 5-axis configurations. The machining centre can be used standalone or can be integrated in a manufacturing cell since it can be interfaced with part handling systems such as pedestal robots, overhead gantries and robots, floor-level track-mounted robots, and fixture storage and delivery systems.

Gruppo Riello Sistemi S.p.A., a large Italian company operating worldwide, designs and manufactures rotary table transfer machines, flexible transfer machines and machining centres. The company provides ad-hoc solutions consisting of *modular devices* that enable modification of the access direction of working spindles (e.g. linear or angular slides manually operated); moreover, the possibility to insert additional rotary axes can be designed on demand. The design of flexible transfer lines with rotary tables represents an example of solutions to cope with the need for frequent reconfiguration, as the machine axis can be easily reconfigured together with the fixturing system when a product change occurs. In addition, physical solutions are supported from the software perspective by adopting flexible control through the use of programmable CNC controls, in order to rapidly change control sequences and priorities.

The previous examples addressed the importance of managing co-evolving products, processes and production systems with reference to the production stage. However, also the field of precision metrology is deeply challenged by frequently changing products. Marposs S.p.A. is an Italian company producing measurement systems directly integrated in the machine tool, and off-machine measurement systems divided into pre-process, post-process and final check devices. This company developed *reconfigurable and modular measurement devices,* with a certain degree of flexibility to accommodate product changes. For example, they recently developed an in-line measuring system for a production line machining six cylinder crankshafts. On the one hand, the complexity of the product geometry characterised by a variable section and, on the other hand, the possible occurrence of product geometry modifications, led the company to design modular and reconfigurable gauges. Compared to the basic gauges (Fig. 4.a) equipped with standard armset, the new proposed solution (Fig. 4.b) is able to cover a wider measurement range.



(a) (b)

Fig. 4. Example of (a) basic and (b) reconfigurable inspection devices (courtesy of Marposs S.p.A.).

Therefore, the measurement system becomes reconfigurable and extendible in a short time, by only requiring the system to be set-up when switching the production between two different part types. In this way product changes in shape and dimensions, in a given range, can be handled.

1.1.3. Digital Enterprise Technologies (DET)

The need for software tools supporting product engineering and manufacturing across the life-cycle represents an additional crucial element of the product, process and production system co-evolution. Because of the complexity in tackling product design and manufacturing as a whole, software tools are traditionally designed to focus on specific issues and tasks. This practice has drawbacks when considering requirements of networked collaboration [15] and concurrent engineering for the design of products, processes and production systems. In this case, a major challenge is to enable the integration and harmonisation of the knowledge of the company through the use of multidisciplinary and varied software tools [16]. This topic is addressed both by the software providers and scientific community; for example, the European project “Virtual Factory Framework” [17] aims at developing an integrated framework to implement the next generation virtual factory, that is constantly synchronised with the real one [18].

The development of software tools has to address two strategic issues to cope with the co-evolution problem:

- Heterogeneous information related to products, processes and resources has to be handled over time, covering the product, process and equipment life-cycles.
- Integrated and open Information and Communication Technology (ICT) architectures are necessary for effective utilization of different software tools to enable the consistent flow of information across the factory.

These two aspects address the problem of growing *complexity and variety of required knowledge* which renders monolithic software, traditionally developed to support a well-defined family of activities and tasks, inefficient in a dynamic environment. Indeed, there is still a strong boundary between knowledge and software tools supporting the product and process design and knowledge and software tools which focus on the product manufacturing and the required system equipment.

The knowledge about the product and process design, generally recognized as Product Life-cycle Management (PLM), supports designers, manufacturers, vendors and sales partners in handling product information across its lifecycle. Among software tools supporting PLM, it is possible to identify:

- Tools for modelling, analysis and simulation of products and processes, such as computer-aided design (CAD), computer-aided manufacturing (CAM), electronic design automation, engineering simulation and analysis among others.
- Product Data Management (PDM) tools that help enterprises manage and visualise product information and processes over time in a collaborative way.

Major companies in the PLM market include Dassault Systèmes, Siemens PLM Software, PTC, SAP and Oracle (ordered by estimated revenue in 2008) [19]. Despite PLM tools embrace the expectation of being a shared platform to capture, represent, and exchange a wide variety of data across all phases of PLM, yet geographic, functional, and cultural boundaries do not ensure that the exchange and reuse of product knowledge across the extended enterprise takes place in the right context [5].

Another problem of present PLM tools consists in the weak link between the product design (CAD/CAM) and product manufacturing, e.g., the process planning problem. Considering the complexity of integrating information on the process with information on the physical equipment and its capability over time, the process planning results in being a knowledge intensive task. This is also reflected by the scarce availability of software tools supporting the generation of process plans (or Computer Aided Process Planning, CAPP) within the PLM platforms. An example of CAM incorporating some features of a CAPP systems is provided by DP Technology Corporation's ESPRIT software. This software has been designed to support the entire scope of process design and planning by integrating a feature recognition engine with the knowledge of the process and manufacturing requirements.

As anticipated, the knowledge and related software tools about the product and the process is generally decoupled from the aspects dealing with the production system design and management. Referring to Numerically Controlled (NC) resources, the so called "CAD-CAM-NC chain" aims at supporting the integration of product and process information with kinematic and functional information on the physical devices within the production system. Currently, there are a limited number of software tools that cover aspects of the CAD-CAM-NC chain and most of them do not incorporate CAPP functionalities. The system design and management tasks mainly deal with process verification and production flow management. The process verification relies on NC simulation systems which detect collisions and visualise the tool-paths. An example of an NC simulator is VERICUT from CGTech. This NC verification software also offers the option of modelling customised machine and component solutions thus supporting the design of new concept and architecture of machine tools and auxiliary devices to match product and process evolution.

The production flow management is traditionally carried out with the support of simulation tools. Some commercial software tools are Plant Simulation, Witness, Arena, Promodel, Automod, Flexsim, Applied Materials, Quest, SCHEDULA, and Simio. However the integration of the production flow management aspect within comprehensive platforms is still a critical issue. A proposal for an integrated simulation tool within a PLM platform comes from Siemens PLM, that developed Tecnomatix™, a tool based on a discrete event simulation engine that enables the simulation and optimisation of logistic flows and resource utilisation for many kinds of production plant and for different hierarchical levels from global facilities to specific subsystems.

Despite the scientific and technical effort invested by the developers of DET solutions, two very critical points still ask for ICT solutions. The first point relates to the limited harmonization and interoperability among different software platforms. This is mainly caused by the lack of standard metadata and the proprietary formats that strongly limit equipment users and producers from efficiently handling factory knowledge. The second aspect deals with the prohibitive costs that are associated with integrated proprietary software suites, which usually penalises SMEs; less structured manufacturing environments are generally characterised by multiple and stand-alone software tools, presenting interoperability problems and loss of data.

1.2. The co-evolution paradigm

A number of production approaches have been proposed to address the aforementioned dynamics in the global market. Additionally, a number of international platforms have been created to facilitate and coordinate the development of the needed methods and technologies shaping modern product development and production. For example, Manu*future* - the European Technology Platform - was established in 2004 to outline the European strategic manufacturing industrial response to the foreseen global industrial revolution, based on research and innovation [1]. Similarly, Intelligent Manufacturing Systems IMS, an industry-led international research and development (R&D) initiative established in 1989 to develop the next generation of manufacturing and processing technologies, recently coordinated IMS2020 supporting knowledge-based platforms to discover common innovations and potential in manufacturing, especially in sustainability, energy efficiency, key technologies, standards, and education [20]. However, the problem of co-evolving products, processes and production systems is still marginally investigated. The launch of the SPECIES Working Group within the CIRP was spearheaded by the need to enhance understanding the fundamental issues of product, process and production system co-evolution, both from the scientific and industrial perspectives. The mission of SPECIES working group was to *investigate approaches, techniques and methods to determine the most appropriate evolution strategy for production system that must competitively operate in an environment characterised by evolving products and technologies*. Fig. 5 embraces the basic principles of the paradigm, named Co-evolution, designed by the CIRP Working Group SPECIES – "Production System Evolution" [7].

The key ideas gathered by the real case studies presented in the previous section are synthesised in the co-evolution vision. Co-evolution involves the repeated configuration of product, process and production system over time, to profitably face and proactively shape the market dynamics namely "changes" in Fig. 5. By properly managing co-evolution a company will be capable of continuously operating at a point that preserves the feasibility and profitability of the transformation process the company performs, in spite of the dynamic context and the uncertainty of available forecasts.

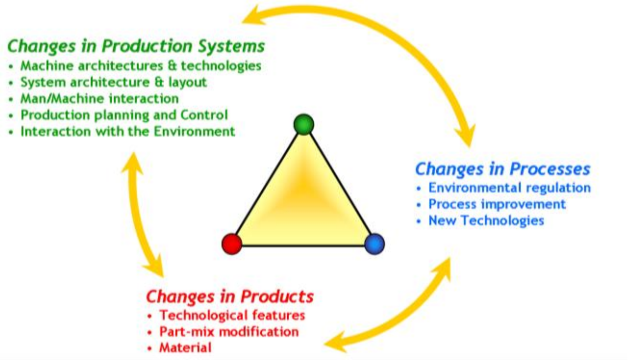


Fig. 5. The Co-evolution Paradigm.

The aim of this paper is to review and systemise the research carried out in the field of co-evolving products, processes and production systems and to focus on specific scientific problems which deserve to be investigated through further research. In this work, the problem will be tackled with a particular focus on production systems manufacturing physical products. The paper is organised as follows. Section 2 proposes and describes the Co-evolution Model. Section 3 presents the methodology adopted for framing the existing contributions in the proposed model. In Section 4, the Co-evolution paradigm is used to analyse the current panorama of methodologies dealing with product, process and system integration and evolution. Section 5 highlights the problems that remain unsolved, thus motivating future research efforts. The strategies and research policies that are currently under development at the national and international levels, as well as the initiatives promoted by organisations and institutions are also reviewed.

2. Proposed framework: the Co-evolution Model

This section describes the Co-evolution Model of products, processes and production systems. The objective of this framework is to formalise knowledge on the Co-evolution paradigm and investigate its applications.

2.1. Objectives of the Framework

The general view of the Co-evolution Model is proposed in Fig. 6. This model delimits a space where Co-evolution management approaches, tools and problems can be mapped, by following a logic and a metric to be explained in the following paragraphs. The geometric model has a prismatic shape with triangular basis. The edges of the prism represent the three configuration entities, i.e., the products, the processes and the production systems. For sake of graphical clarity, in the diagram different colours are associated with products (red), processes (blue) and production systems (green). The vertical axis represents the evolution axis. At any level of the evolution axis, the triangular cross-section represents the integration space among the three entities.

The development of this Co-evolution Model is motivated by the following major needs:

- Formalisation of a new Co-evolution paradigm that is related to the integrated view of products, processes and production systems during their evolution and changes over time.
- Framing of approaches supporting Co-evolution that are suitable to address and solve the specific problems companies in different contexts may need to face (Sect. 2.3.1).
- Formalisation of different industrial problems, considering the impact of the market and the company's organisation (Sect. 2.3.2) as well as the targets that are dynamically fixed and controlled by company strategy (Sect. 2.4).
- Classification of the present state of the art related to co-evolution of products, processes and production systems (Sect. 3 and 4).
- Highlighting of promising research topics for structurally identifying future research priorities (Sect. 5).

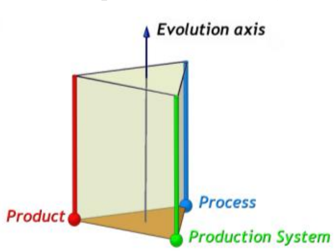


Fig. 6. Graphical representation of the Co-evolution Model.

2.2. Fundamental Definitions

To consolidate the Co-evolution paradigm it is necessary to introduce some basic definitions of the core concepts.

Products, *Processes and Production Systems* are the basic entities on which this paper is focused. The following definitions are consistent with those provided by the CIRP Dictionary of Production Engineering [21] and are targeted to the scope of this paper:

- *Product* is the output of the transformation made by a production system during execution of a process.
- *Process* is the set of basic operations and logical procedures executed by the production system to carry out a transformation resulting in obtaining a product.
- *Production system* is the set of resources, control logics and management policies that allow performing a transformation to obtain a product by executing a process.

These definitions are highly correlated on purpose, to highlight the fact that these three configuration entities are very strongly linked to one another. As shown by the definitions, the transformation is the event that requires interaction among the three entities. Thus, it is not possible to carry out a transformation if one of these objects has not been designed. For this reason, as well as to facilitate reading, products, processes and production systems will be referred to as P^3S.

As noted in Sect. 1, the Co-evolution paradigm involves a deep understanding of the dynamics of P^3S configuration activities that are repeated over time to either follow or push the evolution of the market. The definition of the activity "configure" related to product, process and production system is given by using the IDEF0 formalism in Fig. 7.

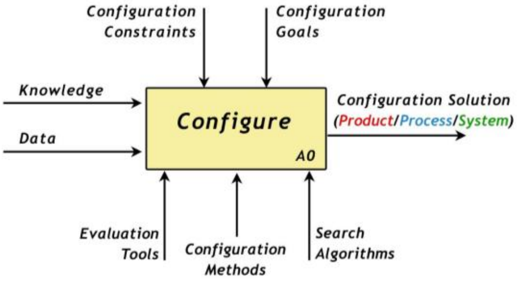


Fig. 7. IDEF0 model for the "Configuration" activity

The *Input* of the activity (Fig. 7, horizontal arrow entering the activity box from the left) is "information", which includes knowledge and data. Knowledge denotes the basic set of rules known to the individual who performs the activity. At this level, nothing is physically defined. For instance, while the process is being configured, the knowledge concerning the technology is the input to the activity. In contrast, data define a specific instance. For example, during process configuration, the product data may be used to generate the process configuration.

The *Output* (Fig. 7, horizontal arrow exiting the activity box from left to right) of the activity "Configure" is a configuration solution, characterised by a detailed and complete set of logical and physical descriptions. The configuration solution refers to one configuration entity, among the product, process and production system.

The *Mechanisms* are the resources used to perform the activity (Fig. 7, vertical arrow entering the activity box from the bottom). For the activity "Configure" these resources consist of evaluation tools and optimisation algorithms. Evaluation tools are used to estimate and quantify some performance measures related to one particular configuration solution. In this way, alternative solutions can be compared based on common performance indexes. For example, simulation is commonly used as an evaluation tool within the configuration of P^3S. Sometimes a configuration activity is supported by optimisation algorithms that facilitate the selection of the most suitable solutions. These algorithms can be based on mathematical programming, expert systems, gradient methods, genetic algorithms, simulated annealing and other soft-computing techniques.

Constraints (Fig. 7, vertical arrows entering the activity box from the top) represent the set of rules limiting extension of the configuration space. The configuration goals define the set of criteria according to which different configuration alternatives are compared.

The activity "Configure" can be carried out by a methodology or an approach.

A *Configuration Methodology* is defined as a procedure used to configure one of the three configuration entities (product, process or production system). The configuration methodology receives data and knowledge concerning one or more entity as input. For instance, Design for Assembly is a configuration methodology used to configure the product with consideration to the input data and knowledge on products and the assembly processes.

A *Configuration Approach* is defined as the entire procedure followed to configure the product, process and production system. Indeed, product, process and system must all be designed to carry out a production transformation. The approach can be unique and integrated or it can be composed of a number of isolated configuration methodologies.

2.3. Integration and Co-Evolution of Products, Processes and Production Systems (P^3S)

The Co-evolution Model aims at analysing both the integration and the evolution level of a configuration approach.

The *Level of Integration* is defined as the ability of a configuration approach to provide P^3S configuration solutions taking into account the product, process and production system data as well as knowledge. The level of integration is related to the input information used to carry out the configuration activity.

The *Level of Evolution* is defined as the capability of a configuration approach to provide configuration solutions considering uncertain information on future evolutions of one or more configuration entity. Uncertainty usually affects either constraints and goals or the input information of the configuration activity.

Even if presented in different sections of this paper, *Level of Integration* and *Level of Evolution* are not uncorrelated metrics. Indeed, integrated approaches are more likely suitable to be adopted in support of the co-evolution of P^3S than are isolated configuration approaches. For instance, consider a case in which changes in product specifications drive the co-evolution process, as shown for Karmann GmbH. If an approach for the P^3S configuration is poorly integrated, it will be difficult to estimate the impact of product changes on the system configuration and to preserve the feasibility of the transformation process in the future. Thus, the co-evolution paradigm is not properly supported by isolated and poorly integrated configuration approaches. This idea is also reinforced by the fact that software providers (Sect. 1.2.3) and researchers (Sect. 4) are currently studying solutions and models for enabling the integrated management of heterogeneous information [22, 23, 24, 25] and knowledge [26, 27] to support P^3S during their co-evolution. Therefore, integration and co-evolution are strongly related paradigms, as further examined and clarified in the next subsections, where these concepts are linked to the Co-evolution Model to meet the objectives stated in Sect. 2.1.

2.3.1. Integration

First, the issues related to the integration of products, processes and systems are addressed. A view of the triangular cross-section of the prismatic Co-evolution Model at a given evolution level (iso-evolution level surface) is shown in Fig. 8. This is called the Integration Space. The objective is to map configuration approaches according to their *Level of Integration*. Following the assumption that a transformation can be carried out only after the three main objects (P^3S) have been designed, first a procedure to map configuration methodologies is proposed. Then, by repeating the procedure for all the P^3S entities, the entire configuration approach can be mapped.

A configuration methodology is represented as a dot that assumes different colours depending on the output of the configuration activity (e.g. green, if the methodology configures the production system). The mapping criterion for a configuration methodology on the diagram is the relative importance of the data and the knowledge on products, processes and production systems within the configuration procedure. Once this relative importance is quantified in terms of normalised weights with unitary sum, a point in the diagram can be identified by using the logic of ternary diagrams. An example of positioning a methodology to configure the system based on normalised weights (0.2, 0.2, 0.6) is represented in Fig. 8.

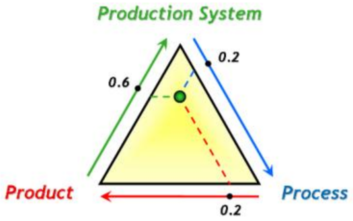


Fig. 8. Example of methodology positioning using ternary diagram logic.

Two options are suggested for determining the weights: the first, based on the experience of the judge, directly provides the vector of weights, whereas the second, more formal and structured, is based on the analysis of a judgment matrix obtained by pairwise comparisons, as in the Analytic Hierarchy Process (AHP) [28, 29]. In both the cases the output of the analysis is a vector of weights determining the coordinates of the configuration methodology. Below are some examples of configuration methodology mappings (see Fig. 9).

$$weights_1 = \begin{bmatrix} 0.6 & 0.4 & 0 \end{bmatrix}$$
$$weights_2 = \begin{bmatrix} 0.2 & 0.4 & 0.4 \end{bmatrix}$$

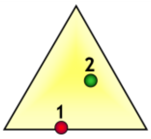


Fig. 9. Positioning of Examples 1 and 2 in the Integration Space.

Example 1 – Suppose a product configuration methodology (red dot is mapped) based on Design for Assembly (DFA) [30, 31]. The methodology allows generating the product configuration starting from a set of input concerning knowledge about the assembly process as well as knowledge and data about the product. A reasonable vector of weights is (0.6, 0.4, 0).

Example 2 – Consider the production system configuration methodology (green dot is mapped) adopted by Karmann GmbH and MCM S.p.A. (Sect 1.2.2) that configure the system using the following input information: product data, production system data and knowledge, process data and related knowledge. A reasonable vector of weights is (0.2, 0.4, 0.4).

As shown, the methodologies use more integrated information as they get closer to the centre of the triangle. Thus, the *Level of Integration* of a methodology is inversely proportional to the distance between its point and the centre of the triangle.

Once a procedure to map configuration methodologies has been determined, it can be extended to map configuration approaches as they deal with the configuration of the entities (P^3S) involved in the transformation. From a modelling point of view, this means locating three dots in the integration space, that are related to configuration methodologies used respectively for products, processes and production systems. Therefore, three vectors of weights (one for each entity) completely define the position of a configuration approach, which is represented in the integration space as a triangular region.

The length of the perimeter of the triangle generated by the three dots is in inverse proportion to the level of integration of the configuration approach. Based upon this consideration, a metric can be introduced for evaluating the *Level of Integration* (*LoI*) of a given configuration approach. Having named i the configuration approach that must be located on the diagram, p_i the perimeter of the region representing the approach, p the constant perimeter of the original triangle (i.e. the whole integration space) and LoI_i the *Level of Integration* of the approach i, the proposed metric is expressed in this equation:

$$LoI_i = 1 - \frac{p_i}{p} \tag{1}$$

The value of LoI_i varies between 0 and 1. If the configuration approach i is poorly integrated, the value of LoI_i is close to 0; if it is highly integrated, its value is close to 1. Below are examples on the use of this metric, showing that it provides a reasonable figure on how integrated an approach is with respect to P^3S information used as input.

***Example 3 – Sequential Configuration*:** The sequential approach is the configuration procedure traditionally used in the past by industrialists. First, the product is configured by using only product data and knowledge (1, 0, 0); then the process is configured by using product data (already defined) and process data and knowledge as input (0.25, 0.75, 0). Finally, the system is configured with product and process given (0.2, 0.2, 0.6). The configuration approach can be located as shown in Fig. 10.

$$weights = \begin{bmatrix} 1 & 0 & 0 \\ 0.25 & 0.75 & 0 \\ 0.2 & 0.2 & 0.6 \end{bmatrix}$$

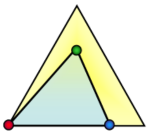


Fig. 10. Weights and position of the Sequential Configuration Approach.

Despite the easy implementation of this approach, the literature highlights its poor effectiveness in rapidly evolving contexts [32, 33] due to the lack of feedback during the configuration process. Indeed, the resulting *LoI* is quite low (0.31), and this approach is probably not suitable for properly addressing the co-evolution problem.

Example 4 – Iterative Configuration: In the iterative configuration approach, continuous feedback concerning the last configuration solutions of two configuration entities are considered when configuring the third entity. This iterative procedure generally ends when no improved configuration can be found for the product, the process and the production system. Fig. 11 shows the matrix of weights and the graphical representation that can be obtained in this situation. The *LoI* calculated for the Iterative Approach is equal to 0.6.

$$weights = \begin{bmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.6 & 0.2 \\ 0.2 & 0.2 & 0.6 \end{bmatrix}$$

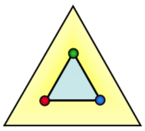


Fig. 11. Weights and position of the Iterative Configuration Approach.

Example 5 – Concurrent Configuration: The product and the process are concurrently configured, considering the available knowledge on the two objects. Then the production system is configured by using product and process data [34, 35]. For instance, in the aeronautics industry the recent trend is to move toward this approach for integrating the product, which traditionally attracted major attention, and process configuration, while the system configuration remains isolated from the previous activities and is typically performed next. This approach is represented in Fig. 12, and its *LoI* is 0.65.

$$weights = \begin{bmatrix} 0.5 & 0.5 & 0 \\ 0.5 & 0.5 & 0 \\ 0.2 & 0.2 & 0.6 \end{bmatrix}$$

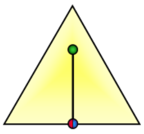


Fig. 12 Weights and position of the Concurrent Configuration Approach.

Example 6 – Collaborative Configuration: The product, process and production system are collaboratively configured, considering the knowledge available about all the objects in a multidisciplinary team [36]. This case is characterised by the vector of weights (0.33, 0.33, 0.33) for each object, and the configuration approach region degenerates into a point in the centre of the triangle. Thus, the *LoI* of such an approach is equal to 1, and full integration is met.

2.3.2. *Impact of Company Organisation*

The company organisation can have an impact on the configuration process by limiting the degrees of freedom of the decision makers. In particular, in a rigid organisation such as a strictly departmental organisation, decisions among product, process, and system configuration are taken by different isolated actors. Generally, they rarely collaborate in teams during the decision-making process [37]. They aim at optimizing their local solutions more than the global solution. In this environment, the use of highly integrated methodologies is almost ineffective and should be avoided, since preconditions for integration are not available internally to the structure. On the contrary, in modern ad-hoc organisations, featuring people collaborating in teams to reach a shared configuration solution according to global goals, highly integrated configuration approaches are very effective and their use should be encouraged, since favourable conditions for integration are present in the company [38].

Furthermore, the role the company plays in the supply chain can have a strong impact on the configuration process. The case of the sub-contractor, already discussed in Sect. 1, is useful to explain this issue. Usually, a subcontractor, especially in the case of SMEs like RCM S.p.A., is not involved in the product design process. This activity is carried out by the companies that sub-contract part of their demand. Nowadays, large companies that have increased the value of their sub-contracting are interested in involving the subcontractors in product configuration activities and in sharing information on their market situation, their customer demand and their forecasts [39, 40, 41]. Indeed, it is a widely held perception that information sharing and effective utilization [22, 42, 43], collaborative design [44, 45, 36], network coordination [46, 47, 48] and risk sharing [49, 50] are key issues towards achieving an effective, production network structure that is responsive to changes [5, 51, 52]. If a similar supply chain structure is adopted, highly integrated configuration approaches may be effective and profitable for the whole network.

Below, we examine how the impact of the company and production network organisation can be represented within the proposed co-evolution model, in order to select approaches that have integration levels targeted to the specific context. The case of unconstrained configuration problems, i.e. absence of limitations by the organisation, is represented in Fig. 13, where the red, blue and green regions represent the spaces where the dots corresponding to the configuration methodologies may fall.

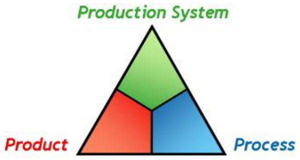


Fig. 13. Admissible region - unconstrained configuration problem.

In a rigid organisation, the product configuration is usually addressed by considering product knowledge. Process and system input data may be available, if these entities have been already configured by other divisions. Therefore, the product configuration region in the model is limited, forbidding the use of process and production system knowledge. Similarly, with respect to process configuration, the only available product and system inputs are specific data, as the process configuration division does not have competence on product and system knowledge. The same arguments hold for the production system configuration. Given these considerations, the *Admissible* and *Forbidden Regions* in the case of a departmental organisation can be represented as in Fig. 14.a. Other types of organisations can lead to different admissible regions. For instance, full integration is possible when configuring each entity in ad-hoc organisations.

The impact of the supply chain organisation can also be represented in the diagram. Focusing on the case of the SME that acts as subcontractor, the product configuration is carried out by using a configuration methodology that can be arbitrarily integrated, since it is the responsibility of a decision maker different from the sub-contractor. Thus, the admissible region for the red dot is the whole red region. Concerning the process configuration, the constraints will act to limit the opportunity of using methodologies integrated in the product direction, whereas integration in the system direction is allowed. The same considerations hold for the system configuration. The *Admissible* and the *Forbidden Regions* are represented in Fig. 14.b.

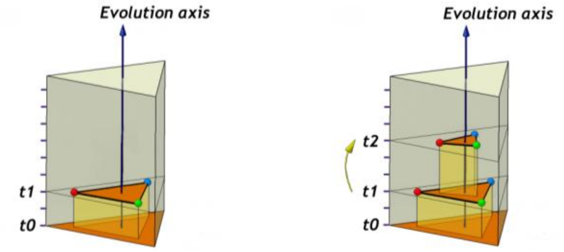
(a) (b)

Fig. 14. Admissible and Forbidden Regions caused by a Departmental Organisation (a) and by the Market in the Sub-contractor Problem (b).

As a matter of fact, what the sub-contractor frequently does is to configure the production system with high flexibility, with the objective of acquiring a required set of process capabilities without making use of product information. A reasonable point for locating the dot corresponding to this system configuration case is (0, 0.2, 0.8). This point falls inside the admissible region.

2.3.3. *Evolution*

The analysis so far has concentrated on integration-related issues given a fixed evolution level. Below the meaning and use of the evolution axis are described, given a fixed integration level. In the Co-evolution Model, the evolution level is represented on the vertical axis (Fig. 15.a).



(a) (b)

Fig. 15. (a) Mapping of a Configuration Approach;.(b) modification of configuration approach required by the Manufacturing Strategy.

The methods and approaches are mapped according to their capability of looking to the future and configuring P^3S, taking into consideration information on possible future scenarios. The further the future information is handled, the higher the evolution level of the methodologies and the higher the 3D prism representing the entire configuration approach in the co-evolution space. The metric used to compare different approaches in terms of the level of evolution (*LoE*) is the furthest time period in which input information useful for the configuration activity is considered. An example follows to clarify the issue. Section 1.2.1 showed that it is not uncommon for companies to face the problem of designing the P^3S while having only uncertain information available on the possible future evolutions of the product requirements. If this information on the future is not considered by the configuration approach, its *LoE* will simply be zero, independent of the value of the *LoI*. However, if the configuration approach allows handling this future information, then *LoE* will be equal to the time of the furthest future information handled by the approach. Examples of methodologies with *LoE* greater than zero are given in Sect. 4.

2.3.4. *Evolution Dynamics*

The output of a configuration approach with a $LoE = t_1$ is a configuration of P^3S to be implemented at time t_0, generated while considering the uncertain information, up to time t_1. However, as time moves from t_0 to t_1, the information scenarios that were uncertain at time t_0 become observable. This phenomenon may require a review of the P^3S configuration decisions at intermediate time stages. Evolving configuration approaches [53, 54, 55, 56] exist that consider check points or solution-review stages along the time axis, thus allowing the modification of the P^3S configuration, when specific previously forecasted scenarios are observed. In the Co-evolution Model, these check points can be represented as tags on the evolution axis. These tags trigger the revision of the P^3S configuration solution considering the observed information outcomes. However, unexpected changes in the external context, market requirements or technological innovations may cause this natural dynamics to be perturbed by external interventions. The strategy is the force that generates perturbation in this path, fitting the application of an evolving configuration approach to the specific configuration problem to be tackled.

2.4. *The Role of the Strategy*

The proposed Co-evolution Model has the advantage of being simple and easy to use for mapping configuration approaches, by graphically representing their features that can be adopted to confront specific co-evolution problems. However, as highlighted in Sect. 1, industry-based reality shows the need of selecting the most suitable P^3S configuration approach for specific co-evolution management problems, that dynamically change over time. Thus, the following questions still remain unanswered:

1. Is a fully integrated and evolving configuration approach the best solution for every manufacturing case?
2. Who sets the *LoI* and *LoE* requirements for selecting a configuration approach for a given manufacturing problem?
3. Who sets the target check points for the configuration approach to update the P^3S configuration solution?
4. Who decides whether or not to generate perturbations to the natural dynamics of applying a configuration approach?

The role of the manufacturing strategy in supporting these activities is presented in the following subsections.

2.4.1. *The Manufacturing Strategy*

"The manufacturing strategy is a plan for moving a company from where it is to where it wants to be" [57]. Operatively, the manufacturing strategy defines a company's manufacturing assets to produce products and implement operations aimed at enhancing responsiveness to market changes. Thus, the manufacturing strategy acts as the higher level controller that drives the dynamic application of configuration approaches to address the specific company co-evolution problem in the best possible way. Indeed, the context in which the P^3S creates value continuously changes over time, calling for a periodic review of co-evolution requirements, settings and objectives. The model adopted by the manufacturing strategy to control the Co-evolution dynamics is shown in Fig. 16.

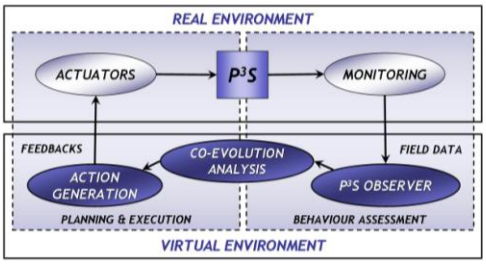


Fig. 16. Dynamics of the Co-evolution of P^3S.

By combining the information provided by the company strategy (higher level controller) and the observation of the current P^3S behaviour, the manufacturing strategy dynamically makes decision on the following feedback: the *LoI* and *LoE* of the configuration approach to be adopted; the constraints to the *LoI* imposed by company strategy and the market; the location of check points along the evolution axis; a need for a perturbation from the natural dynamics of the current configuration approach. Fig. 15.b shows a case in which a given configuration approach, characterised by a certain *LoI* and *LoE,* is modified by the manufacturing strategy due to requirement changes.

2.4.2. *Company Strategy*

A company's strategy has the role of combining the information collected through market observations with the feedback gathered through various strategies including manufacturing and logistics, financial, marketing and R&D, in order to synthesise and generate a business model. The business model collects the set of targets and implementation actions to be delivered to the lower level departmental strategies (manufacturing, financial, marketing and R&D). The dynamics of this outer high level control loop is represented in Fig. 17.

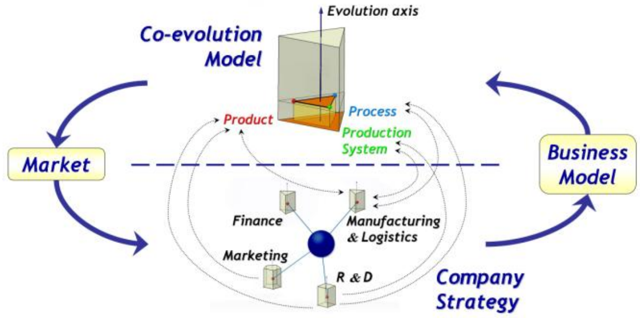


Fig. 17. Outer Control Loop applied by the company strategy.

3. State of the Art Analysis

This section presents the procedure followed to analyse the available literature related to the co-evolution of P^3S in view of the proposed Co-evolution Model. Given the wide scope of this research field, the literature has been systemised using a novel classification methodology (Sect. 3.1). This methodology has been exploited to map the existing literature contributions (Sect. 3.2) and to analyse the current scientific research in this field (Sect. 3.3), as detailed in Sect. 4.

3.1. *Classification Methodology*

The developed classification methodology is based on a multi-level criteria hierarchy. It can be used both to classify new contributions and to analyse the literature once the developed knowledge repository has been populated.

The proposed hierarchy refers to a set of criteria that are targeted to classify papers related to co-evolution. This set of evaluation criteria is organised in a tree structure. During the classification phase, the papers were analysed by expressing the weight (ranging from 0 to 1) of these criteria within the paper itself. This procedure enables the following activities:

- positioning the analysed papers within a common framework coherent with the Co-evolution Model;
- developing an efficient bibliographic search tool targeted to the co-evolution needs (Sect. 3.2);
- systemising the scientific research by supporting the identification of methods with similar features with respect to the co-evolution paradigm (Sect. 3.3).

The criteria are briefly introduced here. Three axes of classification have been defined, covering different characteristics of a paper, namely *Topic* (*X-Axis*), *Evolution* (*Y-Axis*), and *Tone* (*Z-Axis*). Each axis represents a different perspective that can be followed while analysing a paper. A set of criteria or attributes have been defined to specify each axis.

Following the principles of the Co-evolution Model, the criteria tree of the *Topic* axis is as follows: Product, Process and

Production System (Fig. 18). The weights of these criteria can be determined starting from pairwise comparisons like in the Analytic Hierarchy Process (AHP) [28]. AHP allows considering both tangible and intangible aspects and defining the relative importance among them, through judgements by the reviewer.

The pairwise comparisons for the *Topic* axis are carried out answering questions like: The knowledge and data presented in the paper is more related to product or process? Product or production system? Process or production system? Once the weights for the criteria in this axis are calculated, the paper can be positioned in the Integration Space by using ternary diagram logic (see Sect. 2.3.1). The generated weights can be quite subjective, and a better paper evaluation can be obtained if the analyses of different reviewers are merged.

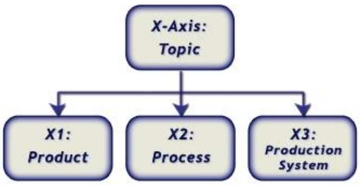


Fig. 18: Classification for *X-Axis*, *Topic* of the paper.

Besides the topic of the paper, it is necessary to assess how the evolution aspect is considered in the paper. The *Evolution* axis is related to this purpose (*Y-Axis*). In Sect. 2 the *Level of Evolution* (*LoE*) was defined as a continuous variable indicating how much an approach takes future information into consideration to configure P^3S. However, classifying the literature contributions in terms of *LoE* along a continuous axis would be difficult and not viable for many papers. Therefore, the *Evolution* axis has been categorised by converting the concept of *LoE* into four values, as outlined in Table 1. The classification of a paper along the *Y-Axis* is carried out by directly selecting one of these values.

Table 1 Classification *Y-Axis, Evolution* aspects in the paper.

Attribute	Description
$Y = 0$	The evolution problem is not addressed by the paper.
$Y = 1$	The evolution problem is discussed in the paper. However, no contribution is given to directly cope with the co-evolution problem. Future information is neither modelled nor managed.
$Y = 2$	The evolution problem is discussed in the paper. The attention is focused on the co-evolution problem and possible solutions are considered, but future information is not managed in a structured way and is not integrated in the analysis.
$Y = 3$	The evolution problem is discussed in the paper. Possible solutions to the co-evolution problem are considered, and future information is integrated in the analysis.

Finally, the *Tone* axis aims at describing which attitude is adopted by the authors to confront the topic addressed by the paper. Four criteria have been defined for this axis, as shown in Fig. 19 and their weights can be determined by means of pairwise comparisons like for the *X-Axis*.

Fig. 19: Classification for *Z-Axis*, *Tone* of the paper.

The next subsections show how the criteria tree was used for the literature analysis.

3.2. Bibliographic Search

A "distance vector" consisting of three components (*Topic*, *Evolution*, *Tone*) can be generated to evaluate the difference between two generic papers. The distance along the *Evolution* axis can be calculated as the difference between two evolution values (*Y-Axis*). The distance along the *Topic* and *Tone* axes can be calculated with equation (2), where *a* is the vector of weights for the first paper, *b* the vector for the second paper, *J* is the set of criteria for the considered axis and 0.5 is a normalisation coefficient assumed to obtain a distance value in the range between 0 and 1.

$$distance = 0.5 \cdot \sum_{j \in J} \left| a_j - b_j \right| \tag{2}$$

A user searching scientific papers according to specific interests can define personal judgements on the importance of the criteria along the three classification axes. For each paper in the bibliographic database, a distance vector is calculated and the classified papers can be filtered by setting a minimum distance from the user preference along each axis. Finally, the user ranks the papers by defining a priority among the axes or by adopting a global distance formula that conveniently takes into account the three components of the distance vector.

3.3. Using the Co-evolution paradigm to classify existing scientific literature

About 300 papers from several international journals have been classified following this procedure. Among these papers, more than 150 have been selected as the most relevant to the co-evolution of P^3S area. In the process, particular attention has been paid to papers addressing the problems related to the configuration of production systems.

All the classified papers can be shown by adopting the graphical representation of the Co-evolution Model (Fig. 20), where the weights of the *Topic* axis are plotted on the Integration Space, whereas the values of the *Evolution* axis are plotted on the vertical axis. From the point of view of the evolution axis, a set of clusters of works can be noticed. These clusters are used in Sect. 4 for a detailed review of those methodologies that are suitable to address the co-evolution problem.

Among the papers not considering the evolution ($Y = 0$), the following clusters of papers have been identified:

A. Papers proposing KM frameworks to integrate product and process information (Sect. 4.1.1).
B. Papers dealing with KM frameworks for integrated P^3S information (Sect. 4.1.1).
C. Papers addressing the process planning problem in a deterministic environment.

Among the papers slightly considering the evolution problem ($Y = 1$), the following clusters of papers have been identified:

D. Papers dealing with the system performance evaluation problem (Sect. 4.2.1).
E. Papers modelling how multi-stage production/assembly processes affect the quality of the product output by means of the Stream of Variation (SoV) technique that models the impact of a process on product variability (Sect. 4.2.1).

F. Papers proposing integrated quality/production logistics models of production systems (Sect. 4.2.1).

Among the papers mildly considering the evolution problem ($Y = 2$), the following clusters of papers can be highlighted:

G. Papers presenting Knowledge Management (KM) frameworks modelling evolving products (Sect. 4.1.2).
H. Papers presenting Knowledge Management (KM) frameworks modelling evolving P^3S (Sect. 4.1.2).
I. Works dealing with production system configuration/reconfiguration methods (Sect. 4.2.2).
J. Papers presenting a biological analogy to analyse and configure the co-evolution of products and production systems/resources (Sect. 4.2.2).
K. Papers dealing with the control of evolving production systems (Sect. 4.3).

Among the papers extensively dealing with the evolution problem ($Y = 3$), the following clusters of papers can be highlighted:

L. Papers addressing the generation of evolving production system architectures (Sect.4.2.4).
M. Papers studying the configuration of co-evolving production systems in an evolving (market) environment (Sect. 4.2.3).
N. Papers dealing with the robust production planning problem (Sect. 4.4).
O. Papers addressing the topic of evolutionary process planning (Sect. 4.5).

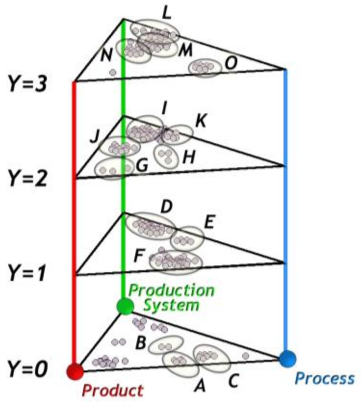


Fig.20. Papers represented in the Co-evolution Model and cluster analysis.

4. Methodologies to Drive the Co-evolution of Products, Processes and Production Systems (P^3S)

This section presents the analysis of the methodologies, approaches and architectures that have been developed to address the co-evolution problem, referring to the clusters introduced in Sect. 3.3. Attention is paid to their position in the Co-evolution Model and their application in industry, with a specific focus on the production system.

One key aspect for co-evolution is the availability of Knowledge Management (KM) methodologies and standards for modelling data related to P^3S during their life-cycle (Sect. 4.1). Another issue highlighted by the analysis of real cases was the lack of unified methodologies to support the production system configuration by considering the P^3S co-evolution. Section 4.2 aims at presenting the available approaches to drive the production system configuration when P^3S co-evolve. Together with the system configuration decisions, also the system control (Sect. 4.3), the production planning (Sect. 4.4) and the process planning (Sect. 4.5) problems are investigated under the co-evolution perspective. Once the methods supporting the configuration of evolving P^3S as a whole are reviewed, the problem of driving the co-evolution problem over time coherently with the manufacturing strategy and the company organisation is addressed (Sect. 4.6). Finally, the steps to bring about the co-evolution paradigm and get benefits in the industry are discussed (Sect. 4.7). Within the abovementioned sections, approaches are presented following a sequence that encompasses the growing capability of the methodologies to handle evolution.

4.1. Integrated Knowledge Management

The complexity and heterogeneity of the information required to address the P^3S co-evolution problem calls for the availability of holistic and highly integrated KM models and standards able to capture the most important relationships among the different objects and variables during the entire P^3S life-cycle. To be effectively used by the industrial and research fields in view of co-evolution management, the KM models for P^3S should share coherent production conceptual models. This problem is still under investigation, though preliminary results on specific areas of knowledge management have been proposed [58].

4.1.1. Knowledge Management for Integrated P^3S

Existing research on the knowledge-based schema and data formalisation models is traditionally developed with regard to products, processes and systems considered as separate entities and, often, focusing on specific field of application such as the automotive or the aerospace sectors.

Most of the existing standards and formalization frameworks regard the product. For example, in the standard STEP "Standard for the Exchange of Product model data” [59], the product information is classified referring to specific product categories, such as mechanical components, ship and electronic products. Also, the Core Product Model - CPM by NIST is a framework developed to represent the product function, form and behaviour as well as its physical and functional decompositions, and the relationships among these concepts [60].

Focusing the attention on the production system information modelling, the major outcomes come from the management field and deal with the organization and business information. ISO 15531, known as the MANDATE standard [61], support the enterprise in modelling the material flow and the information to be exchanged with the other partners of the supply chain (i.e. suppliers, manufacturers, assemblers, and distributors). Recently, the need to incorporate manufacturing information within the production system model, led to the development of standards which represent the physical resources operating in the plant and the processes they are capable of exploiting. Machine tools, cutting tools and auxiliary devices are described with regard to geometric and functional information [62]. Examples of these standards are ISO 13399 titled “Cutting tool data representation and exchange” [63], ISO 10303 - IAR 105 on the kinematic modelling of manufacturing resources [64] and the standard ASME B5.59 [65], which defines information models and formats for describing machine tools for milling and turning based on XML data format.

However, available standards dealing with manufacturing resources often do not consider their integration in the plant, neglecting the understanding of the production system as a whole. This aspect has been investigated only with regard to the soft logics exploited to coordinate the resources operating within the production system by IEC 61499 [66], which is the newly adopted standard for distributed control systems and is based on the IEC 61131 [67] standard for Programmable Logic Controllers (PLC). A more recent activity, concerns the analysis of the production system, seen as a product. This would allow the utilisation of standards, originally developed for the product information representation, for modelling the system resource information. An example is the representation of machine tools with STEP AP 214 [68] and 238 [69].

If compared to the intensive works on both the product and system information representation, the scientific and technical activities dealing with the problem of harmonising product, process and system aspects still present many grey areas. Concerning the product and process information integration ISO 14649 [70], also known as STEP-NC, aims at providing a model for product and process data exchange across the CAx chain, specifically between CAD/CAM systems and CNC resources. A conceptual reference framework consisting of an object-oriented model based on UML language has been proposed in [71] as an attempt towards complete integration of the P^3S knowledge. The basic idea is that the interoperability among various tools to support the decisions in the production environment relies on a common conceptual framework.

4.1.2. *Knowledge Management for Evolving P^3S*

The achievement of an interoperable and digital factory based on the Co-evolution paradigm requires systemising the knowledge of the entire manufacturing environment over time.

Most of the knowledge-based schemas, available in the literature, regard the modelling of the product lifecycle and product evolution, as described by the Product Family Evolution Model (PFEM) by NIST [72] and the standard STEP-PLCS (Product Life-Cycle Support) [73]. Within the product lifecycle problem, some studies are more specifically targeted to the modelling of lifecycle information for aerospace products. Because of the extremely long lifecycle which on average characterize the aerospace products, the importance of systemizing and preserving 3D-CAD and PDM data over time is imperative. With this regard, the associations ADS-STAN (AeroSpace, Defence and Security Standardization) and ProSTEP developed "LOng Term ARchiving – LOTAR" [74], which is a standardization project driven by the some major players in the aerospace sector (i.e. Airbus, Alenia Aeronautics, BAE Systems, Boeing, EADS-Military Aircraft and MTU Aeroengines). In [25] a STEP compliant knowledge-based schema is proposed, called AeroFRAME, to comprehensively represent evolving manufacturing entities and to focus on advanced manufacturing technologies in the aerospace sector. In [75], a general conceptual object-oriented framework is proposed for the integrated modelling of evolving product, process and production system data. However, a comprehensive analysis of current standards and formalization frameworks still highlights the very little number of works dealing with co-evolving P^3S.

4.2. *Configuration of Co-Evolving Production Systems*

Configuring a production system by considering a deterministic environment and neglecting information on the future requirements may yield lower performance over the system life-cycle or, in the worst cases, even infeasibility of the transformation due to the market uncertainty, as evidenced by the industrial cases in Sect. 1.2. Therefore, to support the configuration of co-evolving production systems it is crucial to describe, model and analyse the uncertain future information. Next, the existing approaches to support the configuration of co-evolving production systems under uncertainty are described.

The description follows the point of view represented in Fig. 21, which is inspired by the discussions in [76] and [6]. In the figure, the production system configuration perspective is taken; thus the "green" system layer is emphasised. However, similar layers also exist for the product and the process which do in fact interact with the production system configuration layer. At the higher level (box at the top of the figure), the generation of the system architectures and the configuration of the production modules is addressed. As pointed out in [77, 78, 79], modularity, compatibility, scalability, universality and mobility are the principles that the production module designer can follow to provide change degrees of freedom to the production resources. From a logical point of view, these features represent the change enablers [78] that allow the system to modify its structure and capabilities when needed. During the design of these modules, typically creative [80], co-creative and emergent [81] approaches are followed. Indeed the boundaries of the specific production problem are not yet defined. The designed production modules populate a database of available technical solutions and architectural rules (box on the left side of Fig. 21), to be used by the next design phases to specify a detailed system configuration, customized to the specific production problem. The generation of production modules enabling the co-evolution of the production system will be addressed in Sect. 4.2.4, since the analysis requires a fairly high level of evolution.

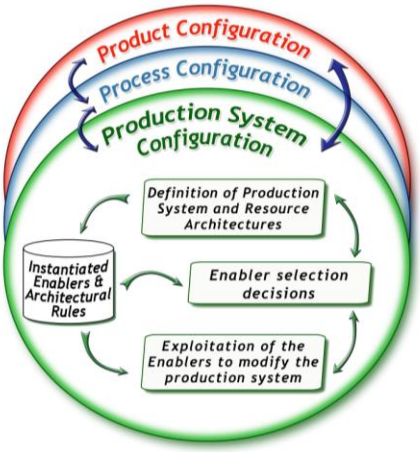


Fig. 21. Phases of the configuration of co-evolving production systems.

The second phase of the co-evolving system configuration process typically involves decisions concerning the selection of technical enablers among those generated in the previous phase. In this phase, the configuration requirements are known over the referenced planning horizon. The methods to support this activity are presented in Sect. 4.2.3.

The third phase addresses the exploitation of the system change enablers to run the system at the operating conditions which better suit the market requirements. This problem is typically well defined, and uncertainty does not play a relevant role. Thus, the methods used to address this problem generally present a fairly low level of evolution. In this phase, the methodologies consist in external procedures (Sect. 4.2.2) that trigger a change in the system configuration and internal performance evaluation procedures (Sect. 4.2.1), which in turn explore and evaluate the system configurations options to select the best one.

The aforementioned phases (Fig. 21) are not isolated, but require continuous interaction during the system life-cycle. Whether the designed change enablers are not sufficient to face unforeseen scenarios, then a feedback is generated from phase 3 to phase 2, thus requiring to redesign the system change enablers.

4.2.1. Performance Evaluation of Co-evolving Production Systems

The goal common of all the methods described in this section is, given a specific system configuration, to estimate a predefined set of production system performance measures that may be the actual configuration of a production system or a virtual configuration generated by an external procedure. Various methodologies have been developed to evaluate the performance of co-evolving production systems, above all analytical methods, simulation and logistics operating curves.

Analytical methods have been developed with the aim of evaluating production system performance by proposing a mathematical model of the dynamic behaviour of systems. The main advantage of these methods is that, on top of providing a fairly accurate estimation of the system's main performance measures (e.g. throughput, work in progress, lead time), they are also useful in explaining phenomena related to the dynamics of the material flow in the system. Thus, they are not to be considered as "black box" evaluation tools, but rather as manufacturing system analysis tools. The drawbacks of these approaches lie in the rigid assumptions required to mathematically model the system behaviour. This is the case of exact analytical techniques based on queuing theory [82]. To overcome this problem, approximate analytical methods have been developed [83, 84]. Efficient approaches have been proposed to evaluate the performance of production lines with serial layouts [85], systems characterised by non-linear flow of material [86], and multi-product production lines [87]. Recently, a new technique called Two Level Decomposition has been developed for evaluating generally complex system layouts [88].

Simulation is characterised by high flexibility, since it can handle any degree of detail describing the system behaviour. As has already been pointed out in Sect. 1.2.3, several commercial software packages supporting the development of customised simulation models through pre-defined architectures and templates are already available. Distinct from analytical methods, simulation can be considered as a "black box" tool. Thus, even if, in principle, one could build a simulation model customised for this requirement, the main role of simulation does not consist in providing explanations about the cause-effect propagation dynamics in the system. Moreover, while increasing the level of system complexity, it requires considerable modelling effort, and, typically, long simulation runs.

Logistic Operating Curves (LOC) [89, 90] are methods that extract knowledge on system behaviour from production data by making use of simple structural relations between different system performance measures, to support the user in the difficult task of operating a system in a configuration that profitably exploits the characteristic trade-offs. These curves can in principle be derived from simulation, real manufacturing data and analytical results. They support the user in the decision making via easy-to-read quantitative graphs showing the dynamics of the material flow in the system.

Simulation, analytical methods and logistics operating curves are all characterised by a fairly low level of evolution. For these methods to be effective in support of co-evolution, they need to be coupled with external analysis procedures that generate patterns of systems with modified parameters whose performance has to be evaluated to find the best changes to address the co-evolution. Another limitation when considering co-evolution is that the aforementioned performance evaluation methods typically rely on models that lack the ability to integrate product and process information. Thus, they can be applied during co-evolution only within an iterative configuration approach (Sect. 2.3.1). Recently some contributions moving towards the integration of product/system and product/process information have been proposed.

Grounding on production system background, integrated models and analysis tools for quality and productivity performance evaluation of manufacturing systems have been recently proposed [91, 92, 93]. These models integrate product specifications, process out-of-controls, machine failures and typical logistics parameters such as finite buffer capacity and complex routing of parts. Analytical methods are then applied to estimate integrated quality and productivity performance measures, including effective throughput, system yield and scrap or rework fractions. Applications of these methods have shown interesting phenomena due to the trade-off between quality and production logistics performance, such as the existence of optimal buffer sizes that maximise the average throughput of conforming parts. These methods do not consider in details the impact of the quality of the output of a process on the downstream processes. Nonetheless, this process/product interaction is a major challenge within manufacturing industries, due to dimensional product variations. Two-thirds of all process design changes during the launch of a new assembly process in the automotive and aerospace industries are caused by dimensional failures/variations [94]. To deal with this problem, the approach known as stream-of-variation analysis (SOVA) was developed by Jin and Shi [95], Ding et al. [96] and Ceglarek et al. [97] for rigid parts and extended by Camelio et al. [98] for multi-station processes with compliant parts. Huang et al. [99, 100] extended the SOVA model to 3D cases. A detailed description and review of the SOVA model with applications to quality control for multistage manufacturing processes is presented in [22, 101, 102]. The SOVA model helps predict the propagation of variation in the assembly process due to fixture failure and has since led to the development of variation fault pattern diagnosis [103, 95]. The SOVA model has also been used to determine adjustment in multi-station assembly processes [104].

4.2.2. Use of the System Co-Evolution Enablers

The procedures to trigger system configuration modification by using existing system co-evolution enablers can be classified as reactive and proactive. Reactive procedures trigger the production system modification after a change in one of the other two entities has been observed (product and process), while proactive procedures trigger a modification of the system when performance improvement is required.

Hu et al. propose a reactive procedure to properly address the co-evolution of production systems and products, based on the reusability principle. Ko et al. [105] define *manufacturing system reusability* as the capability for a system to be repeatedly applied from one generation of products to another after the initial use. Their approach considers production systems that have the modularity to be organized into many different configurations, e.g., serial, parallel or hybrid are considered. Koren et al. [106] and Spicer et al. [107] evaluated the performance of these systems, showing that different configurations can have a profound impact on quality, throughput, responsiveness and cost. When planning for the co-evolution of products and production systems, it is necessary to select the configuration that maximizes re-use of the machines and resources in the system from one product generation to another.

A different approach is considered in [12, 13], where the configuration of co-evolving manufacturing systems is formulated as an optimal control problem. The available degrees of freedom of the system are described as ranges in the multi-variable space of system functionalities or in the system capacity. The future evolution of one or more of the P^3S is modelled as statistical distributions. The methods, based on the *dynamic programming* technique, generate control limits that may trigger system modification when the available system functionality [13], or capacity [12], is not sufficient to profitably process the modified products.

The themes of evolution and co-evolution have motivated some researchers to study the analogy between evolution in manufacturing and nature. The concepts of *Biological Manufacturing Systems* (BMS) [108] and so-called interactive Manufacturing Systems [109] have been proposed to deal with unexpected changes in the manufacturing environment based on biologically inspired ideas such as self-growth, self-organization, adaptation and evolution. These concepts can be exploited to dynamically consider system reconfiguration problems [110] in adapting to changes in product demand and to system resource malfunctions, as external and internal disturbances. ElMaraghy [111] proposed a new tool for tracking the evolution courses of products akin to the evolution of biological species. *Cladistics* visual hierarchal data analysis was used to establish the analogy between evolution in manufacturing and nature. This innovative concept is capable not only of separately modelling the evolution of products or their manufacturing systems, but also their symbiotic co-evolution relationship. It reveals the effect of evolution on product family grouping. This tool was also incorporated in a twofold analysis; (1) a cladistic depth analysis that derives guidelines for symbiotic product/system design by identifying the promising product features favoured by product evolution [112], and (2) a cladistic breadth analysis to identify the potential opportunities for product design modularization and sustainable evolution [113]. A co-evolution framework of products and manufacturing systems proposed by AlGeddawy and ElMaraghy [114] suggests a reciprocal co-evolutionary relationship where new product features require more manufacturing capabilities, and new manufacturing capabilities represent new opportunities for product designers. This co-evolution framework was translated into an in-depth study of the mechanism and objectives of evolution of both products and manufacturing systems in the machine tools history [115]. The study showed that association and symbiosis in manufacturing may take one of two forms; (1) disruptive - when new manufacturing paradigms, materials and technologies are introduced, and (2) gradual - where small modifications in product design are handled by small incremental changes in manufacturing systems. This biologically inspired product/system co-evolution mechanism is mathematically formulated in a three-stage model in [116], and case studies from automotive engine accessories are used to demonstrate the benefits of the approach.

A product life-cycle perspective is proposed in [22] to trigger manufacturing system modification to react to the identification of in-tolerance product failures, observed in the product service phase. Ceglarek et al. [5] proposed a *self-resilience* framework for closed-loop product life-cycle to improve product quality and process robustness. Self-resilience refers to a system's ability to self-recover from changes and faults in design, manufacturing and service. The key aspects of the self-resilience system are information and knowledge integration between different product life-cycle phases and a systematic methodology to address unforeseen faults and changes. First, it entails integrating information and knowledge within the same phase of the product life-cycle to enhance the robustness, diagnosability, and adjustability (called *intra-loop*). Second, it involves the information and knowledge integration between two or more phases of the product life-cycle (called *inter-loop*). An example of an analysis method for intra-loop modelling and industrial applications is the *SOVA* approach already described in Sect. 4.2.1. The *inter-loop* modelling framework between service and manufacturing phases is used to eliminate the *in-tolerance* failures, such as No Fault Found (NFF). The in-tolerance NFF failure refers to faults reported by customers when the product undergoes service-related tests at a service centre and no fault is identified [117]. The NFF phenomenon is a major problem when dealing with complex products and contributes on average to 45% of reported service faults in electronic equipment, up to 50% for aerospace industry [118], 63% of the faults in cell phone manufacturers [119] and more than 50% in automotive industry [120]. To deal with in-tolerance NFF failures, Mannar et al. [121] developed a *Functional Region Localization* (FRL) methodology which combines warranty and manufacturing data to identify and localize in-tolerance faulty regions. However, definitive solutions to remove/avoid in-tolerance failure may include product/process re-design and manufacturing process adjustments [122].

In [123] a coupled *two-loop control framework* is proposed to proactively trigger the reconfiguration of an evolving production system with modular buffers in the automotive industry for performance improvement purposes. The classical process-resource control loop is coupled with an external system control loop that triggers system modification when there is poor alignment between the target performance and the measured performance. The signal activates the application of a series of production system models in sequence, where the core module consists of decomposition-based analytical methods for virtual modelling of the real system and for rapidly testing different optional reconfiguration actions. The parameters of this model are tuned through the analysis of the data available in the production monitoring system. Next, two models for system optimization and sensitivity analysis allow testing specific system improvement actions involving reconfiguration before implementation, also quantifying their impact on observed performance. Finally, the pattern of system modifications that, using the system degrees of freedom, allow adjusting the observed performance on its target value are synthesized and implemented.

All the methods presented in this subsections deal with bounded ability of system modification, since change enablers are given. Therefore, the need for dealing with uncertain future information is limited, and their degree of evolution is typically fairly low. On the other hand, integration of product, process and production systems information is extremely important and in general highly considered by existing approaches.

4.2.3. Selection of the System Co-Evolution Enablers

The approaches addressing configuration of the production systems co-evolution enablers under uncertainty typically model the uncertain future as scenarios [78], 78]. Thus, they usually present a relatively high evolution level, because they look to the future to cope with the uncertainty and formalise the information scenarios. If the evolution is modelled by means of a *scenario tree* [124], then *Real Options Analysis* [125] or *stochastic* *programming* [126] can be applied. Models and tools are needed to plan the evolution of manufacturing system design and reconfiguration based on knowledge of future products evolution and development trends as well as likely production volume and variety. Several researchers tackled this problem and developed models for achieving a smooth and optimal transition between system configurations with limited knowledge of future evolution developments [55]. The output is a map of the system (re)configuration decisions planned for different future scenarios at different decision stages. According to the number of times the decision maker can revise the designed system solution, it is possible to model single-, two- or multi-stage problems.

Tolio [127] has proposed a manufacturing system design approach that is structured as a set of steps belonging to different research fields, such as manufacturing strategy, process planning, system design, capacity planning and performance evaluation. Within this approach, Terkaj et al. [128] have presented a methodology to design *Focused Flexibility Manufacturing Systems* (FFMSs) [76, 129, 130] by identifying the set of decisions regarding the acquisition and dismissing of resources to achieve the maximum expected profit over the system life-cycle, while referring to process, functionality and capacity constraints. This methodology is based on stochastic programming and solution techniques based on problem decomposition [131, 132] can be adopted to address its inherent complexity. Referring to the Co-evolution Model, the FFMS configuration method incorporates the concept of integration. The present and future system configurations are planned by considering integrated and evolving information on product and process.

Another approach that uses simulation for the evaluation of alternative system configurations under different product demand scenarios is proposed by Kimura [133]. This methodology considers the *system's adaptability* to changes together with its cost for investment and operation. Starting from demand curves generated by forecasts, several scenarios of product evolution are defined. When the future product demand pattern is generated, the production system life-cycle pattern is also generated by considering the different possible system reconfiguration capabilities and production volume requirements as constraints.

4.2.4. Definition of the Production System and Resource Architecture

The design of innovative solutions of machine tools and production systems generate as outcome a set of system change enablers. *Reconfigurable Manufacturing* and *Assembly Systems* (RMSs and RASs) are examples of system architectures featuring change enablers [77, 134]. In these systems, open architecture controls and modular machine tools are integrated [135, 136]. Recently, a new generation of machine tools has been designed with multi-spindle apparatus, modular machine frame and reconfigurable inspection systems [137, 138, 139]. The need for change enablers is also translated in auxiliary devices operating in the production and the fixturing systems [140]. Fixture calibration in RMS and RAS is complex as reconfigurable tooling elements need to be calibrated in multiple positions. Kong and Ceglarek [141] presented an integrated approach for rapid reconfigurable fixture deployment based on (1) *Fixture Workspace Synthesis* and (2) *Fixture Visibility Analysis*.

Although several modular production resources solutions have been recently proposed, formalised procedures to generate new families of evolving systems are almost unavailable. A major issue is the design of the production modules, as the performance of these resources strictly depends on the specific configuration of the whole system. A better integration of the design of product and system change enablers can help in this activity, as suggested in [80] where, driven by the interaction between customer preferences and the re-allocation of modular manufacturing resources, viable product families emerge from a variety of technically feasible product alternatives.

4.3. Control of Evolving Production Systems

The ability to adapt to changing requirements is dependent on the ability to manage the uncertainties in the manufacturing context, including changes in part geometry, variances in raw materials and disturbances affecting the behaviour of physical devices within the plant. To support system co-evolution, control systems should ensure that uncertainties in manufacturing tasks are managed effectively, from the MES to the single CNC, and that the factory efficiently meets the production requirements. A major challenge in developing adaptable and evolving manufacturing systems is the rigidity of the existing control systems which could become obsolete while the manufacturing environment evolves. Recent studies have been carried out to specify, design, implement and evaluate distributed adaptive control systems for manufacturing enterprises [142, 143]. They are designed as dynamically reconfigurable control systems to continuously adjust production requirements.

A major bottleneck for production systems that need to be frequently reconfigured to carry out changes in production requirements is found in the scarce integration between MES and SCADA (*Supervisory Control And Data Acquisition)* systems of the factory as well as their poor modularity and flexibility [144]. Traditionally, the shop-floor control is organized in a hierarchy of control computers, which is hard-wired and rigid in the software structure. Current software architectures are designed to support the integration and communication of MES and SCADA systems as they are organized in dynamically cooperating modules or entities organised as a decentralised structure [145], 1002]. In this regard, Agent Technology can support the development of open, dynamic, agile, scalable and fault tolerant systems [146], as an agent can be designed to accomplish tasks such as distributed process monitoring and execution control by negotiating with other entities to determine local and global objectives [147]. In addition, innovative methodologies to design reconfigurable control systems start to refer to interoperable and learning multi-agent systems MAS [148]. In complex production environments, characterised by frequent changes of products, processes and production plans, the ability to detect change and interpret how it can be managed based on past experience, would allow incorporating intelligence in the factory.

4.4. Production Planning and Scheduling under Uncertainty

The actual performance of co-evolving production systems strongly depends on the effectiveness of production planning and scheduling methods in adapting to changing features of P^3S. Planning decisions are deeply influenced by changes related both to the context (e.g. demand variations) and to the production system itself (e.g. resource configuration, capability and availability). Most existing software tools do not provide a complete representation of the evolutionary problem and are based on simplifying hypotheses (e.g. infinite capacity of the resources) that limit their applicability in dynamic contexts, thus reducing company confidence in using these tools. A set of techniques can be adopted to cope with uncertainty and modifications while configuring production plans, that are suitable to the scope of co-evolution.

Robust production planning approaches aim at protecting the performance of the devised production plan against the occurrence of unexpected events and P^3S changes. Robustness in planning and scheduling can refer either to the cost of the plan or to the plan itself. In the first case the term “quality robustness” is used, whereas in the second case “plan robustness” or “stability" is adopted [149]. Robustness of the production plan strictly relies on the possibility of modifying the timing of the activities with little or no penalty on the company objective function value.

Reactive production planning and scheduling approaches focus on the strategy to react and “repair” the plan when uncertain events occur [150]. Alternatively, proactive approaches incorporate information about the possible occurrence of uncertain events in the plan, developing a predictive plan capable of absorbing changes while maintaining high performance and limiting re-planning [151]. Neither approach, however, is sufficient to devise an acceptable robust production plan. On the one hand, reactive approaches do not consider information or forecasts about uncertain events, thus proposing a schedule that can be very hectic in highly variable environments; proactive approaches, on the other hand, model uncertain events but without trying to separate the single effects, often resulting in an overly cautious plan. Therefore, a challenging issue in robust planning consists in developing an approach that retains the benefits of both reactive and proactive approaches. Stochastic programming [152] seems to be a promising approach for achieving this goal [153, 154, 155].

In the co-evolution vision, the function of *real-time production scheduling* is to adapt the short term production plans to the evolving P^3S features while preserving efficiency with respect to cost, time and quality requirements. The first key issue is to develop intuitive and flexible models and fast, reliable solution techniques that also scale-up well to large production scheduling problems[156]. These models should be flexible enough to deal with various sources of uncertainty like changing resource capabilities and processing times, capacity availability, unspecified activities due to evolving problem definition, hypothetical orders and unreliable delivery dates of necessary components and materials. Any method that neglects these issues is prone to generate fragile solutions. However, the direct inclusion of any main uncertainty factor in realistic models is not feasible because of complexity reasons. Nevertheless, the sensitivity of deterministic solutions can be assessed and the robustness of production schedules can be improved by using discrete-event simulation techniques [156, 157].

Secondly, real-time scheduling has to be integrated both upwards and downwards in the hierarchy of planning and execution control functions [158]. While production planning determines what to do in the medium term, scheduling is responsible for refining a segment of the production plan into a detailed and executable schedule. However, since the two levels use different models, production plans often cannot be unfolded into feasible and executable detailed schedules. This calls for frequent re-adjustments, suboptimal performance and system nervousness.

An alternative to the traditional, hierarchical planning-scheduling-execution control scheme is the application of a decentralized, multi-agent system [147]. The PROSA reference architecture [159] augmented with coordination and control mechanisms inspired by natural systems guarantees that production plans are properly executed under changing conditions, while it continuously forecasts the manufacturing resources workload and product lead times. This design empowers the product instances to drive their own production; hence coordination can be completely decentralized. In contrast to many decentralized designs, the manufacturing execution system predicts future behaviour and takes proactive measures to prevent impending problems from happening [159].

4.5. *Evolutionary Process Planning*

Production planning (Sect. 4.4) can help to cope with unstable demand and internal unexpected disruptions such as breakdowns, dynamic bottlenecks and unforeseen changes of jobs priority, but the ability of a production system to evolve can be heavily jeopardised if it is not supported also by the evolution of the process plans. As a matter of fact, the present structure of NC codes is still nearly rigid, and the part programs require relevant changes when the production plan is modified (e.g. an operation is assigned to a different machine), or the production system is reconfigured (e.g. a flow line substitutes a job-shop), or the product evolves (e.g. removal/addition of a product feature). Therefore, evolving processes require methodologies to enable the rapid generation of process plans and their easy adaptation.

The generation of reconfigurable and adaptive process plans can be supported by adopting a *Nonlinear Process Plan* approach that consists in relaxing constraints that are not strictly technological [160, 161]. The resulting network of operations, compared to the traditional rigid sequence, enables to (1) execute the operations according to various sequences and on different machines [162], (2) quickly reconfigure process plans [163] and (3) develop new loading and scheduling methods [164]. Recently, the topic of nonlinear process plan has been extended to the generation of part programs, by developing the concept of Network Part Program (NetPP) [10] that has been already implemented by machine tool builders (e.g. by MCM S.p.A.).

There are a number of studies dealing with the development of *reconfigurable process plans*. These are mostly based on identifying similarity between new or evolved products and existing ones as well as on algorithms for optimizing the process precedence graphs. In [165] a generic constraint-based model for CAPP has been proposed together with appropriate solution methods and applied to different industrial domains [166, 167].

A further approach to reconfigurable process planning has been recently developed focusing on (1) minimizing the parts handling and re-fixturing time and (2) minimizing the cost of changes in the evolved process plan referring to setups, tools, re-programming costs [168]. In addition, evolving process plans have an impact on device configuration, especially in reconfigurable manufacturing systems, as illustrated in [169].

4.6. *Control of the Dynamics of P^3S Co-evolution*

One of the key aspects of co-evolution is the need to reduce the gap between the inertia of production systems life-cycle and the frequency of changes in products and processes. Over a broader time than considered in the previous sections, higher level controllers that continuously and profitably drive the P^3S co-evolution dynamics are required (see Sect. 2.4).

4.6.1. *Factory Control*

From the control perspective, co-evolution planning is a task requiring a good understanding of the complex factory dynamics. In particular, the ability to *foresee* if the current P^3S configuration can cope with upcoming or anticipated disturbances is of fundamental importance, because evolution strategies can be triggered in the case a gap is identified. *Predictive* dynamic models are now commonly used, where the model response at time “t” contains trajectories of values that span some future horizon “t+p”. *Model Predictive Control* (MPC) is the typical advanced control strategy which makes use of such predictive modelling. Predictive control strategies can be integrated into a hierarchy of controllers, each at a different functional level. In one approach the entire production enterprise is subdivided into higher level strategic, middle level tactics, and lower level production layers [170]. Important variables at each layer are modelled and controlled using different MPCs. Interactions among variables at different layers are also possible by cascading different MPCs. Two performance criteria are defined for the predicted controller outputs: one for the spatial dimension and one for the temporal dimension. In the former, a value saturation (VS) is defined if a set point cannot be tracked within some specified tolerance. In the latter, a time saturation (TS) is defined if the set point cannot be reached within some specified time horizon. The link between co-evolution and such predictive control is nicely established by continuously monitoring the VS or TS tolerances and by defining some threshold over which the necessity for evolution is triggered. Challenges for implementing such a generic approach include synchronizing the different time scales at each layer, adapting continuous control theory to discrete part production [171], distributing the required control information over the existing networks, adapting the higher level planning models to a control-based formulation and validating the predictive models with real data (output feedback).

Other approaches for predicting and controlling the complex dynamics of the production layer are also reported. In [48] a dynamic state space model of production networks with *autonomous work systems*, each having local capacity control, is proposed. The model is a one step prediction of the orders input, output, actual WIP and capacity. It can be used to dynamically optimize the routing of orders [172] (see Sect. 4.4).

For complex dynamical systems, data-driven models are also used. In [173] a neural network learns the production layer dynamics from historical plant data and decides the subsequent routing of orders among potential autonomous worksystems. It was shown that the level of autonomy influences the logistic performance [174] (see Sect. 4.2.1).

4.6.2. *Production Network Coordination*

Markets are typically served by production networks that consist of autonomous enterprises. Partners are legally independent entities, with their own resources, performance objectives and internal decision mechanisms. In Sect. 2.3.2 it was shown how the production network structure can seriously constrain a company’s ability to manage P^3S co-evolution, preventing from integrating P^3S information and sharing P^3S evolution patterns. To avoid this effect, there is an inevitable need to design organizations to respond to changing market demand by sustaining coordination and, if possible, cooperation among network members [47], [175]. For instance, the above goal has been achieved in a work by Monostori et al. aimed at improving the performance of a production network that produces low-tech customized mass products [176]. Specifically, so as to make partners interested in cooperation and in truthful information exchange, an incentive scheme was developed that facilitates the sharing of risks and benefits when acting together in supply planning [52].

Problems with the current state of coordination, management, design and redesign of global supply chains have also been identified in [51]. These problems make effective configuration and modification of the global supply chain difficult and result in a rigid and poorly adaptable organization. Recently, new ideas for exploiting the benefits of the co-evolution of the product, process and production system at the production network level have been proposed by Wiendahl [177]. Wiendahl showed through a real case example that the problems leading to long completion time of a product, which are due to the great number of process stages and the large variety of product components can be suitably addressed in the global supply chain through effective product structure re-design. Specifically, the product can be re-designed in order to produce standardized components at the early stages and to assemble customized components when a demand is observed. The re-engineering of the product enables companies to manufacture components with great added value at production sites characterized by highly skilled personnel and highly capable systems and to delegate production of low technological content parts to less efficient sites. This tendency affects how the production system is designed at different sites and requires dedicated solutions at the early stages of production and flexible solutions at the product customization stages. This example shows how modern production network management approaches can make use of the co-evolution concept to profitably address the globalization challenges.

4.6.3. *Manufacturing Strategy*

Manufacturing strategy is a high level controller driving co-evolution dynamics. Early works on manufacturing strategies poorly embrace the dynamics characterising the current manufacturing environment and the need to concurrently handle product, process and production system related problems [178]. A first effort consistent with the Co-evolution Model has been proposed by Voss [179], suggesting a continuous loop where a company defines a strategic vision that needs is persistently revisited. A more recent framework is the *Agile Manufacturing* paradigm [180, 181], based on the company ability to create processes, tools and training to quickly match customer needs and market changes while still controlling costs and quality. The enabling factor in becoming an agile manufacturer is the development of manufacturing support technology that allows designers and production personnel to share data on products, production capacities and problems across the supply chain.

4.7. *Implementation of Co-evolution*

The following subsections describe the issues related to the implementation of the co-evolution paradigm in the manufacturing industry, focusing on the main challenges and benefits for companies, communities and society.

4.7.1. *New Business Models*

The development of new business models is an innovative concept in the machine tool industry. Until recently, equipment suppliers were traditionally oriented towards offering machine tools with a limited number of additional product-related services. However, as the co-evolution management problem has increasingly taken centre stage for production system users, machine tool builders have started conceiving the notion of innovating their business models towards establishing long-term relationships with their customers and providing value-added services beyond the technical products [182]. This collaborative approach is a key issue for implementing the co-evolution paradigm for production system users and constitutes a significant business opportunity for production system producers.

The *selling-use* approach was theoretically conceived by Franke et al. [183] as an alternative to the classical "equipment selling" scheme for systems characterised by high reconfigurability. More recently, research on Industrial Product Service Systems (IPS^2) has been launched within CIRP [184], with the objective of investigating benefits and operating modes for implementing the product-service idea in industry. A recent attempt towards the implementation of such concepts has been made in the European project "NEXT" [185], where new collaboration and financial models were designed to facilitate the profitable implementation of solutions to specific co-evolution problems. Examples of these financial and collaborative models are *Pay per Availability, Pay per Part, Lean Machine Adaptation Service* and *Production Service* [186]. Even if this idea is unanimously accepted by equipment producers, it is still far from being implemented [187]. The main reason has been identified as the lack of a specific managerial culture and of operating tools supporting this profound change; research results currently available to the companies are mainly at the strategic and conceptual level. Indeed, the link between strategy and concrete operations is still weakly exploited.

4.7.2. Complexity and Co-evolution

The literature frequently reports that manufacturing systems are becoming increasingly complex in their layout, control policies, material flows, information flow, etc. [188, 189]. Furthermore, it has been shown that systems featured with the ability of evolving (reconfigurable, adaptable or flexible systems) have inherently higher level of complexity than rigid systems. However, it can be argued that some of this complexity is due to the difficulty in correctly managing the co-evolution problem, especially concerning material flows and layouts. If a production system is designed only for a predetermined set of part types and available processes and its context is characterised by rapidly changing products and technologies, the system user is forced to constantly modify the system architecture. When a production system does not have enough degrees of freedom to allow modifications of its structure, its complexity then increases over time, since subsequent modifications are added to a rigid structure. This results in factories that are extremely difficult to model and manage. However, if the degrees of freedom are available and are properly exploited, co-evolution can then be profitably managed. In this case, the implemented changes do not consistently affect the possibility of further modifying the system in the future. Thus, system complexity increases less than in poorly co-evolving systems and may even decrease for particularly favourable market conditions. This phenomenon has been pointed out in recent publications on the analysis of complex systems [190, 191, 192] and is particularly visible in real industrial cases [193]. Therefore, proper implementation of the co-evolution paradigm may help reduce the complexity of the factory, thus facilitating its modelling, analysis and control.

4.7.3. Reconfigurability, Flexibility, Adaptability, Changeability and Co-evolution.

Although the concept of co-evolution has only recently been investigated in the research arena, synergies can be found with well known paradigms of reconfigurability, flexibility, adaptability and changeability. In [78], a comprehensive framework was proposed where these paradigms were modelled as different classes of changeability. According to [78], reconfigurability is the operative ability of a manufacturing system to switch to a particular family of part types, whereas flexibility is somehow a broader concept involving the tactical ability of the entire production and logistics areas to switch between families of components. This definition is consistent with the vision proposed in this paper (Sect. 4.2), even if a slightly different point of view is emphasized. In the co-evolution view, both the flexibility and reconfigurability concepts are related to the ability of a manufacturing system to absorb changes with minimal effort and delay by modifying the production system structure. However, whereas in *flexibility* this ability already exists in the system, in *reconfigurability* this ability can be acquired by using the existing change enablers of the system, when needed. Change enablers are the core concept of the provided definitions of flexibility and reconfigurability. The definition of the change enablers is a fundamental contribution of the *changeability* paradigm. Changeability is more general than the previous paradigms, since it provides the theoretical foundation for explaining the dynamics of change for objects ranging from a single station to the entire production network. Another paradigm frequently used to refer to the ability of a system to change is *adaptability*.

In this panorama of modern production paradigms, the key contribution of the *co-evolution* vision can be summarized as: (I) the concept of integrating product, process and production system information to profitably drive their evolution by preserving the coherence among them and coordinating the different inertia of their life-cycles, and (II) the idea of the co-evolution trajectory that is controlled by the manufacturing strategy and constrained by the market and the company's organizational conditions.

4.7.4. Guidelines for Industrial Applications

The proposed co-evolution model is presented in this paper to systemize the analysis of the existing literature in the field of co-evolving products, processes and production systems. However, it can also be used by industrialists to develop a co-evolution oriented manufacturing strategy and to select the most suitable methods and tools to address specific co-evolution problems. The analysis begins by formalizing the production problem of the company with respect to the relative importance of the product, the process and the production system in the company market. In this paper, examples are given of highly product-centric sectors, e.g., the aeronautics sector, and system-centric industries, e.g., the market of mechanical component subcontractors in the automotive sector. Evaluating this relative importance, which may be carried out in teams of experts following the AHP approach (Sect. 3), is relevant for ensuring agreement between the manufacturing strategy and the company market. This activity would result in the selection of a core region for the company in the integration region of the co-evolution diagram. Moreover, the market constraints and the organizational constraints should be analyzed to identify forbidden regions of the co-evolution model, as proposed in Sect. 2.3.2. These activities characterize the co-evolution problem in terms of target P^3S integration level. Next, the proper evolution level of the methods to be selected should be analyzed. In the co-evolution model, the evolution level is strictly related to the time horizon covered by the foreseeable P^3S information. As increasing level of uncertainty is associated with future information, reliable information is necessary before addressing the co-evolution problem. The analyzed degree of integration and evolution determines a core zone in the 3D co-evolution model that characterizes the boundary of the company co-evolution problem. It would then be possible, using the tool presented in Sect. 3, to select the group of methodologies that are closer to this core zone and may help the designer to address the specific co-evolution problem in a structured way.

4.7.5. Co-evolution and Research Policies

The underlying concepts of the co-evolution model have been clearly addressed by European research policies and road maps. The European Association for the Factories of the Future (EFFRA) [194] was created in 2009 and serves as a special purpose vehicle for implementing the Public Private Partnership on “Factories of the Future” with the European Commission, with the mandate to assess and manage research in manufacturing over the coming years. The strategic multi-annual roadmap clearly states: “Knowledge based innovation in products, processes and systems is the key concept to sustain European competitiveness: innovation leading to a new life-cycle based product-service, manufactured in a sustainable way, responding to the needs of customers and society must be promoted” [195].

5. Future Research Priorities

The classification methodologies and the results illustrated in Sect. 3 and Sect.4 have been used to identify regions of the co-evolution model where methodologies are lacking and problems deserve attention by the research community in the future.

*Standards for evolving P^3S information***.** Despite an attempt had been made in the literature to develop conceptual models to integrate product/process information and to use product frameworks to model system information, the integration of evolving P^3S information remains difficult to be modelled under a knowledge management view, thus representing an open research issue. A major bottleneck stays in the possibility to consistently integrate a multitude of existing standards without being constrained by the specific industrial applications.

Reconfigurable Process Plans. CAPP represents the area where information about product and process design (CAD/CAM) needs to be coupled with information about available manufacturing resources to generate process plans. In production contexts characterized by frequent changes, the need to be supported by reconfigurable CAPP systems is imperative. However, the development of tools to support automatic reconfigurable process plans for evolving P^3S is challenged by the need for integrated information and a comprehensive knowledge about the actual manufacturing environment.

Generation of new evolving system architectures. Section 4.2.4 has shown that the generation of technical solutions and system architectures that embed change enablers is nowadays addressed by creative configuration approaches, as the boundaries of the specific problems to be address are not well defined. With this regards, structured methodologies to build the architecture requirements by analyzing the product type and process features would be important to the system architecture designer. This may lead to the conceptualization and proposal of new system architectures specifically customized to the solution of co-evolution problems. New business models to profitably support the joint design of product and system architectures based on the collaboration between manufacturing system users and producers may also be developed and tested.

Process evolution enablers. Considerable effort has been spent toward the design of evolvable production systems and products. However, the process still constitutes a bottleneck in the achievement of co-evolving P^3S and only few process change enablers have been developed (e.g. non-linear part-programs). Currently, the impossibility to change the order of execution of operations, to optimize the operation sequence in real time at shop floor level and to split a specific part program on different machines calls for innovations in process reconfigurability to adapt to evolving production requirements.

Control of P^3S Co-evolution. Section 4.6 has shown that although theoretical approaches for supporting the control of Co-evolving P^3S have been developed, operative methods for controlling the co-evolution dynamics and the timing of co-evolution related decisions are not available. These methods should consider the targets fixed by the manufacturing strategy and trigger activation of co-evolution analysis whenever a modification is needed.

Co-evolution risk analysis. The assessment of the risks associated with the implementation of different co-evolution strategies is an area of research that is practically unexplored. Section 4 highlighted the importance of highly evolutionary methods that treat uncertain future information in the design of co-evolving systems. However, the designer needs to estimate the risk related to the use of this information to generate the P^3S co-evolution trajectory in order to fairly compare different co-evolution solutions. This aspect is typically neglected today due to lack of structured risk analysis method.

New business models for Co-evolving P^3S. Section 4.7.1 reported on the most advanced business models related to the co-evolution of P^3S. In this area, open issues include the development of software tools for diagnostics and collaborative re-design of evolving systems, the development of models for information sharing between the service provider and the users and the design of new business models to exploit the possibilities enabled by the formalization of the co-evolution principle. Moreover, the consequences of the adoption of new collaborative business models should be further investigated, including financial aspects related to the ownership of production resources, economical aspects of sharing product/system design costs and issues related to intellectual property rights.

6. Conclusions

This paper overviews the current achievements in the field of co-evolution of products, processes and production systems. The integration of product, process and production system information profitably drives their evolution by preserving the coherence among them and coordinating their life-cycles. The co-evolution trajectory is controlled by the manufacturing strategy and constrained by the market and the company organization conditions. A model has been proposed to formalise co-evolution problems in different industries. The presented real cases show a clear industrial trend toward the management of co-evolution, perceived as economically beneficial. However, the variety of approaches adopted in industry highlights a poorly structured decision process behind the selection of the best approach and a lack of dominant design methodologies. The co-evolution problem can be addressed by various scientific approaches , and SPECIES has contributed to sharing a common vision on the problem. Based on the proposed Co-evolution Model, several open issues have been highlighted that are functional to implementing the co-evolution principle in modern industries and require basic research efforts to be addressed.

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