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Modular and platform methods for product family design: literature analysis

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After the industrial revolution, the literature has mentioned different "principles" to allow a better management of the production and product life cycle activities. For example the principle of standardization was first mentioned in the literature by an automobile engineer and placed in a real context by Henry Ford. Standardization has made possible the configuration of different products using a large set of common components. Another strategy called "modularization" was first mentioned in the literature in the 60s. The modularity proposed to group components of products in a module for practical production objectives. Today, modularity and standardization are promising tools in product family development because they allow to design a variety of products using the same modules of components called "platforms". Using platforms allows important family design savings and easy manufacturing. In this paper we give a literature review of the platform concept with a special interest on the efficient product family development. This paper is organized as follows. Section 1 mentions the general context of modularity to develop product variety. Section 2 details the importance of product architectures in the literature for a modular design. Section 3 points on some important works that apply some modular and platform methodologies.

Keywords: Design optimization, flexible manufacturing, modular design, product family design, product platforms

1. Context of modularity to develop product variety

Several works mention that the development of a variety of products is a complex activity (Meyer and Lehnerd, 1997; Zamirowski and Otto, 1999). Usually the costs of special components are high: the production line has to deal with special processes, specialized machine tooling, specifications, tolerances, additional staff efforts, more setups and, in some cases, new layouts. Fulfilling the customer requirements is expensive from a manufacture point of view.

In this sense, Thyssen and Hansen (2001) mention a useful classification of the strategies to customize and develop different quantities of product demand. This classification is shown in Fig. 1.

Developing modules of components in the design is a strategy that helps customizing a large variety of high demand products. This aspect is called "Mass Customization",[1] as opposed to "Flexible Manufacturing" which is oriented to the process, the use of modules is a strategy oriented mainly towards the design. Modularization is an approach to organize complex designs and process operations more efficiently by decomposing complex systems into simpler portions. It allows the designer to play with combinations of groups of components to develop and customize a larger quantity of products. This concept was first mentioned in the manufacture literature by Star (1965), who proposed the use of modular products in production as a new concept to develop variety.

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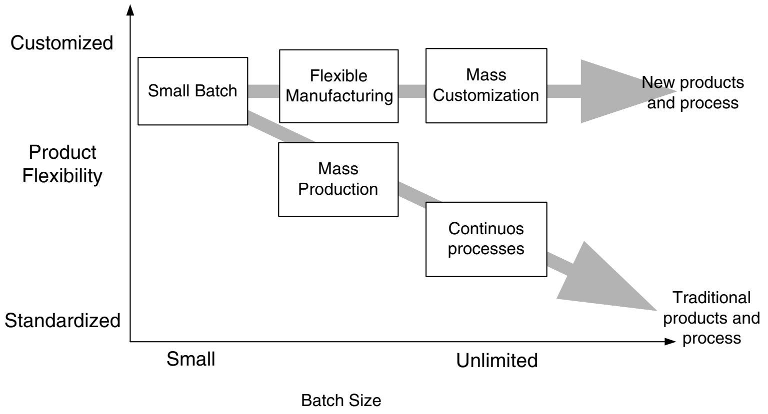


Fig. 1. Strategies based on the quantity of product demand and level of customization (Thyssen and Hansen, 2001).

The decomposition of complex systems into smaller and more manageable parts has also been discussed in management and economic literature.[2]

In engineering literature, there are formal definitions of modularity for example:

- A module is a group of standard and interchangeable components (Galsworth, 1994).
- A module is a complex group that allocates a function to the product and which could be changed and replaced in a loose way and be produced independently (Wilhelm, 1997).
- A modular system is made of independent units which can be easily assembled and which behave in a certain way in a whole system (Baldwin and Clark, 1997).
- The term modularity is used for the expression of common and independent parts for the creation of a variety of products (Huang and Kusiak, 1998).

According to the Fig. 2 by Elgård and Miller (1998)[3] the number of products that can be developed depends on the number of module versions and variants and their physical coupling characteristics (interfaces) which allow the possibility of combining them.

1.1. *Platforms*

The use of a standard module between different products is known as a platform. The use of the same module helps adapting few differentiation components and making few adjustments to develop a limited variety of products. Refer to Fig. 3. as an example. A suspension system can be used for different products with only few components additions. A "platform" has implications like the use of common manufacture process, technology, knowledge which are shared by multiple products in a family. In this sense the decision of which modules and assets are going to be unique or standard between products obeys to a complex costs analysis. A good analysis should not only consider an easy platform adaptation to develop other products or economic benefits of easy conception, but also the maximization of economic benefits of the reduction of the number of the total of different assets.

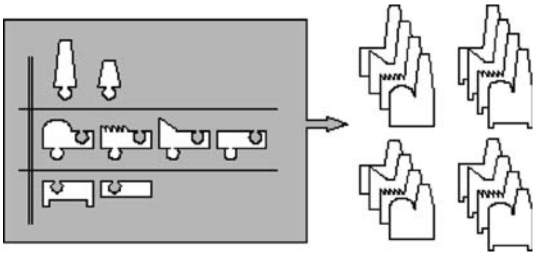


Fig. 2. Combination of variants of modules to offer a level of variety. Each module has different versions and interface specifications (Elgård and Miller, 1998).

Some works mention the way to standardize different products modules of the same level of the bill of materials (Thomas, 1991; Fujita *et al.*, 1999). These works are good tools for the selection

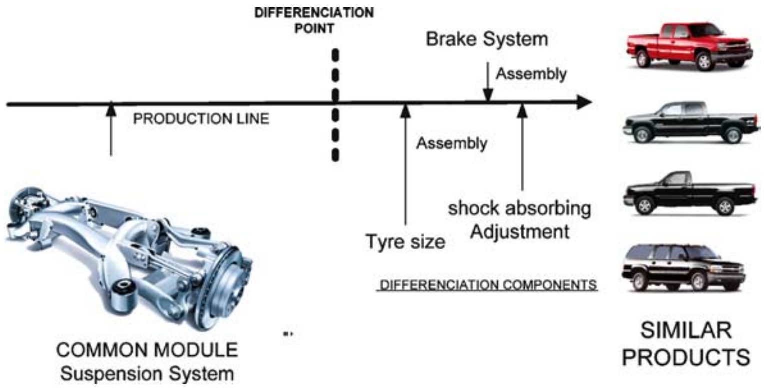


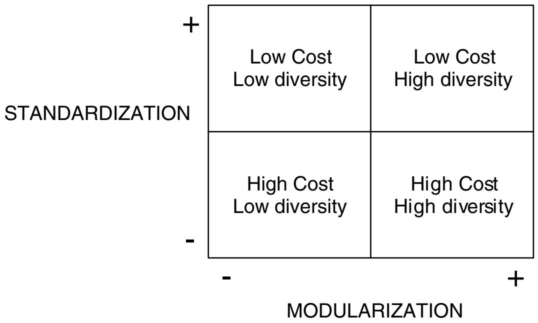
Fig. 3. The products share the same platform. Product differentiation by few component parameters.

of components within a platform, since finding a group of common modules would allow us to organize standard manufacturing operations at the beginning in the production line and differentiation manufacturing operations later in the production line, characteristic called "Postponement". The first manufacturing operation to differentiate the product is called "Point of differentiation". The interest is to use a maximum of common components at the beginning of the production line to postpone the point of differentiation later in the process. Few differentiation operations located late in the production line will allow to react faster towards high demand and high product variety. Some works related with delayed differentiation can be found in (Lee and Tang, 1997; Martin and Ishii, 1997; David *et al.*, 1998).

The selection of a platform needs a comprehensive balance of "the number of special modules vs. number of common modules". The dilemma in this sense is: the company should optimize and customize precise products with special components or should use standard components to satisfy market variety needs? This would be translated to the trade-off "Product Differentiation vs. Standardization".

The use of different modules allows to realize a greater number of combinations resulting in more diversity of products but also increasing the cost. The use of more commons modules than different modules reduces the number of combinations but allows costs savings. The principal advantages and disadvantages of these aspects are exhibited in Fig. 4, we could consider "Modularity" in the matrix as a synonym for the use of more different modules and more "Standardization" as the use of more common modules.

An analysis of the Fig. 2 allows to conclude two ways to increase the "Modularity": one is the division of a module version into small parts, the other is to include more module versions. To reduce "Modularity" one way would be the accu-



STANDARDIZATION	MODULARIZATION -	MODULARIZATION +
+	Low Cost Low diversity	Low Cost High diversity
-	High Cost Low diversity	High Cost High diversity

Fig. 4. Impact of cost having different levels of modularization and standardization.

mulation of modules in a bigger module the other would be the reduction of module versions. Figure 5B shows how to increase the level of "Modularity" in relation to the Fig. 5A. Dividing a module in small modules will allow eight combinations of modules. The Fig. 5C shows how to increase the module versions and thus standardization.

According to the Fig. 5 the level of standardization and modularization can be manipulated without affecting one or another. Thus the level of modularity and the level of standardization could be independent. In relation to this, the trade-off evaluation should be focused to finding a maximum of standard components without affecting the ability to develop the necessary products.

The matrix mentioned in Fig. 6 could be used as a guide to evaluate and identify a module as standard or differentiation module.

According to (Jiao and Tseng, 1999) the selection of a module as standard or differentiation, depends on its utility to product distinctiveness and on its cost.

Relative cost measurement

The relative cost measurement of the module can be based on the facility that is obtained by using the module to adapt other modular products. Such evaluation includes the cost of product life cycle activities. This type of analysis is exposed in more detail in José and Tollenaere (2004). The lector can refer to Ulrich and Eppinger (2000) or Pahl and Beitz (1988) for a general guide of product development or product design considering other product life cycle activities.

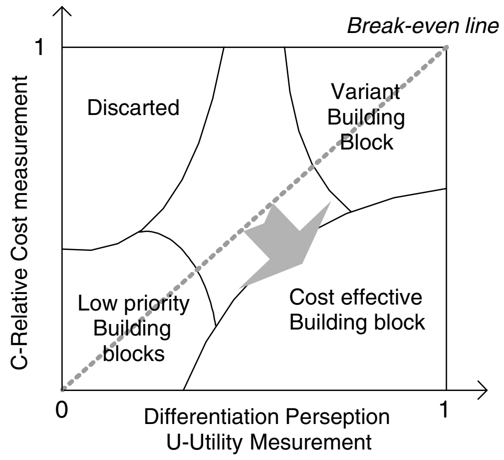


Fig. 6. Module evaluation as standard or differentiation module (Jiao and Tseng, 1999).

The design based on the product lifecycle activities, has been a theme of research since 1990 which is usually called design for "X". For example Veeralamolmal and Gupta (1999) mention: Design for Assembly (DfA), Design for manufacturing (DfM), Design for Environment (DfE). In modular design we can also find: Modularity for Conception (MID), Modularity for production (MIP), Modularity for Use (MIU), (Baldwin and Clark, 2000).

Utility measurement

The utility could be considered as the influence of the components on the product performance and their aesthetic characteristics. The measurement of this impact is one of the principal problems in the research on standardization.

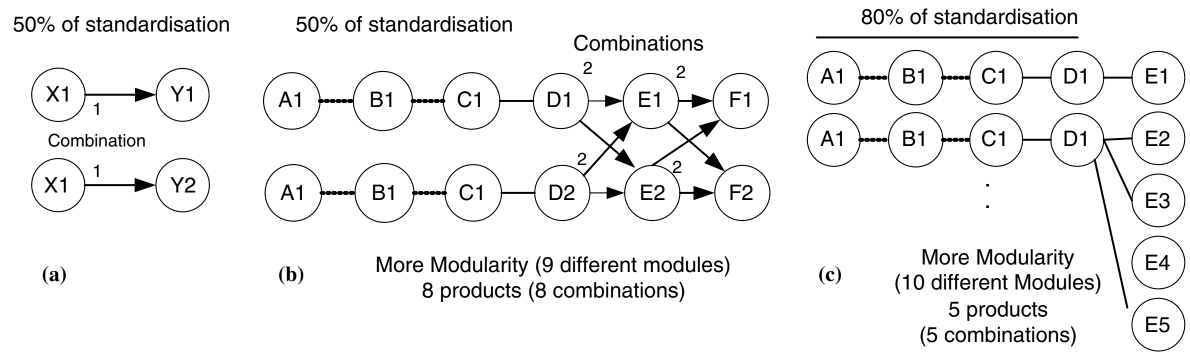


Fig. 5. Assembly of versions of modules.

In synthesis, in relation to this kind of works, it is considered important to answer to the following questions:

- It is possible to identify modules in an existent or inexistent design?
- Can we identify standard and differentiation modules in the design?
- Can we make an efficient balance of these two types of modules in the design according to the different advantages?

1.2 *Organizational aspects*

In addition to the conception aspects, working with modules requires to consider several implications about the organization. Managing modules to design other products needs a careful analysis because any update or design choice have an influence on future manufacture and management activities, thus affecting the company performance criteria's, for example:

- the number and type of assembly requirements in the production line
- the way the modules are supplied
- stock costs
- components and material savings
- operational reprocessing
- transport costs
- the way the product is repaired, bundled, packed, recycled,[4] etc..

Designing modular products requires more commitment by the key members of the company and product life cycle actors, since it needs more expertise, coordination, efforts, time and is more expensive than the design of classical products because it considers the conception of several products at the same time. The efforts and costs are concentrated at the initial period as illustrated in Fig. 7.

According to this figure, there is more time expended to develop a family in a classical way than to develop a family with modules. This allows to consider that if the variety of product is low it may not be necessary to spent time and great efforts to match modules to develop different products. Optimizing and designing products in the individual form (integral design) could be faster and a better option. If there is a great variety of products in the family then it would be faster and cheaper to design different products with a set of modules.

A modular design can be justified for a faster product development for subsequent derivative products. The company can develop families not only because the use of the same modules saves time, but also because specialized discipline groups can work more efficiently on modules related to their discipline.

Sanchez and Mahoney (1996) give more general organizational implications of modules management. Garud and Arun (1995) give some organizational implications about information systems and capitalization of knowledge when managing modular designs.

2. Product architecture

Several works consider the product architecture as the baseline for product family development, (Jiao

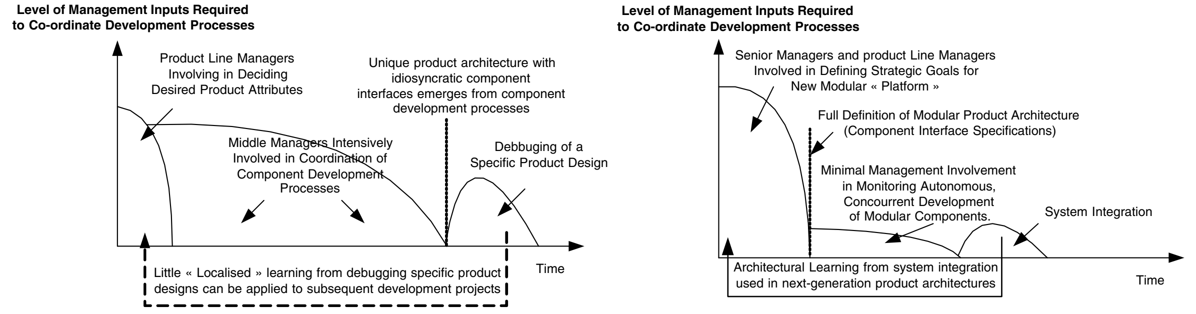


Fig. 7. Comparison of management effort and organizational learning in traditional vs. modular product development processes (Sanchez and Collins, 2000).

and Tseng, 1999; Dahmus *et al.*, 2001; Mikkola and Gassmann, 2001; Otto, 2001).

2.1 *Definition*

Ulrich (1995) says that the product architecture is the scheme where the physical components are associated to functional elements to form different products. Ulrich and Eppinger (2000) explain these two dimensions in the architecture: the *functional* one, which is the group of operations and transformations that contributes to the general functionality of the product, and the *physical* one, which refers to the group of physical components and assemblies that enables a function. The architecture could be considered as a configuration between components of the product and the tasks that each component should do.

According to Ulrich and Eppinger (2000), the architecture is established after the definition of the market target, the products technology tendencies and the identification of all the general family product specifications. The architecture is defined according to the Fig. 8, between the concept development phase and the design of system levels (assembly hierarchies).

Ulrich (1995) distinguishes two types of architectures:

1. The modular architecture where a relationship "one to one" exists between functional and physical elements, determining loose coupled interfaces between components in such a way that architectural changes on one component do not lead to changes in other components (in a functional and physical way). A easier understanding work about components and functions relationships is made by Chakrabarti (2001). Usually the type of module architecture has to be coherent with the company strategies, as for example product upgrading, product performance, manufacturability and product component costs.
2. Integral design: it is a fixed architecture oriented to an optimized product. It is the classical product design where changes to one component cannot be made without

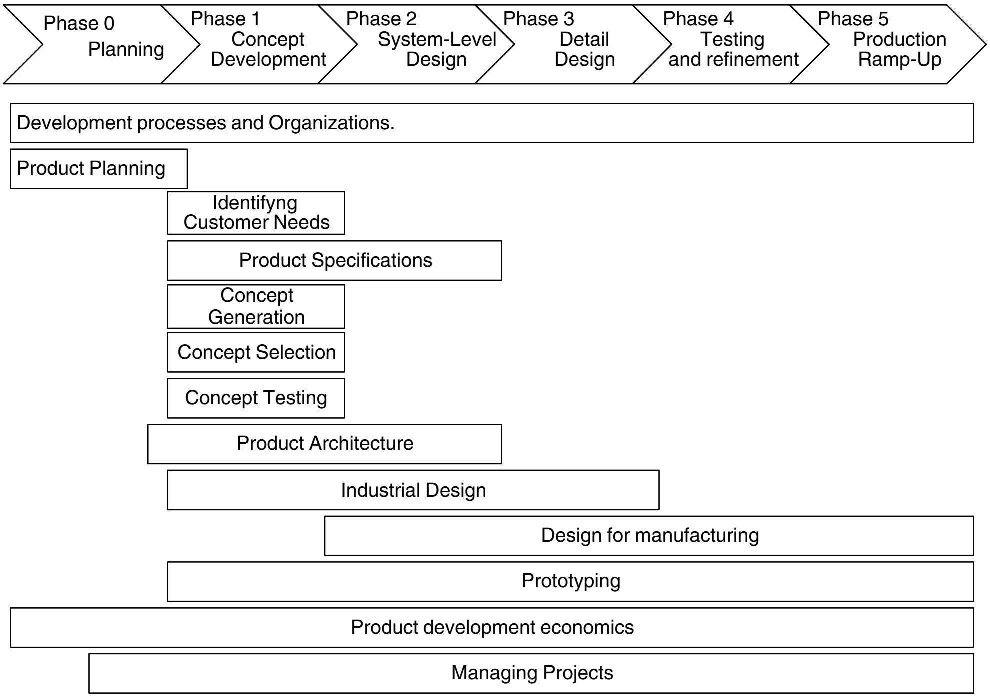


Fig. 8. Product development process (Ulrich and Eppinger, 2000).

interfering with others. Its design includes complex relationships (not one to one) between components and functions, and complex interfaces connecting components.

Some benefits of these two architectures are listed in Table 1. Some other general advantages of modular architectures are discussed in Huang and Kusiak (1999).

2.2. *Modular architectures*

In modular products there is a special interest in the product architecture literature. Mikkola (2000) says that the product architecture is the arrangement of functional elements in building blocks and it could be developed by defining a mapping of functional and physical elements considering interface specifications between components or modules. These works consider that a module has the characteristic to provide one or a group of functions to the product. Defining modules considering their interfaces allows giving functionality to the product and easily adapting or eliminating a group of functions from the product architecture.

After defining the product characteristics, the architecture analysis allows to select common and different components to find common and changing functions between products.

It is easy to find some works focused to finding modules which consider some rules. For example Stone *et al.* (1998), Zamirowski and Otto (1999) mention different rules to develop a product architecture. Ulrich and Eppinger (2000) also gives 4 steps to establish modular product architecture:

1. Create a scheme of the product: develop a conceptual model of components and functions.
2. Cluster the elements of the scheme, regroup components inside of modules in the model according to:

- the assembly precision: two components should be in the same module when they require a precise assembly, to avoid several

Table 1. Tradeoffs between modular product design and integral product design

Benefits of Modular Designs	*Benefits of Integral Designs*
● Module task specialization	● Interactive learning
● Increased number of product variants	● High levels of performance through special technologies
● Economies of scale in component commonality	● Systematic innovations
● Costs savings in inventory and logistics	● Superior access to information
● Lower life cycle costs through easy maintenance	● Protection of innovation from imitation
● Shorter product life cycle through incremental improvements such as upgrade, add-on and adaptations	● High entry barriers for component and module suppliers
● Flexibility in component reuse	● Craftsmanship
● Outsourcing	
● System reliability due to high production volume and experience curve	
● Faster assembly and less production time	
● Postponement of operations of differentiation for fast reaction of the market.	
● Parallel manufacture of modules.	
● Fast development of products	
● Examples: PC, Lego toys, PDA, ink pens.	● Examples: CD, satellites, Formula One cars.

Nevins and Whitney (1989), Corbett *et al.* (1991), Pahl and Beitz (1988), Thomke and Reinertsen (1998) and Mikkola and Gassmann (2001).

precise assembly operations in the production line

- function sharing: when two functions share the same components, these functional elements could be better managed inside a module[5]
- technological similarity: make modules based on the components technological similarity or based on component production advantages
- localization of change: isolate in a module the components with high possibility of change
- accommodating variety: isolate components that are different from one product to another
- enabling standardization: standardize a module if the same components are shared between products. For example the ink cartridge of the jet printers
- portability interfaces: group components that share the same flux type

3. Create a geometric layout: to observe a layout or sketch of the design will help detecting interfaces and modules.
4. Identify fundamental and incidental interactions in the scheme: finding strong relationships in the conceptual model helps finding modules and the groups of persons in charge of modules.

2.3. *Considerations*

The use of necessary components

The specific characteristics of the family of products are obtained using particular module combinations. The group of modules should have the necessary components to fulfill specifications for each product in the family. In this sense, there is a special interest in the content of the modules in a way to avoid or minimize the over-equipment of components. For example Evans (1963) has developed a mathematical tool in this sense, on which are based several other works.

Module configurations

In order to manage modular configurations in the architecture, Ulrich and Tung (1991) proposes six categories of modules relationships: swapping, sharing, bus, cut-to-fit, sectorial, mix. Huang and Kusiak (1998) also offers other modular configurations, he mentions the use of different types of modules: (1) Basic modules: where each module represents a function. (2) Auxiliary module: where each module represents auxiliary functions to create various products. (3) Adaptative modules: when the functions are used to adapt a design. (4) Non-module: designed individually for specific product functions.

These module relationships classifications are applied to different contexts of product development.

Interfaces

An important aspect of module specifications are the interface characteristics. Some authors consider the interface aspect as the base for modular identification, (Garud and Arun, 1995; Sanchez and Mahoney, 1996; Mikkola, 1999, 2000; Mikkola and Gassmann, 2001). The interface characteristics limit the number of modular combinations. For example the compatibility for different configurations of PC's depends on the port compatibility of the modules CPU, monitors, and keyboards. Interface characteristics usually refer to physical coupling specifications. Some authors also mention the material, signal and/or energy specifications.

According to Mikkola (1999) a module could contain sub-modules. A module usually has more coupling constraints than sub-modules. The modular hierarchy dictates the complexity of interface characteristics and the opportunity of "modularization" as shown in Fig. 9. The quantity of specifications and number of interfaces are usually in function of the system size. For example, adapting a big system like a motor to another like the chassis require more engineering efforts to adapt interfaces and coupling specifications than a single submodule.

2.4. *Examples of successful applications*

Some successful examples of modular architecture can be appreciated in the market. For example Swatch watches are assembled with different modules: the cover, the bracelet, etc. The changes only affect parameters like the color and the size which make the difference on the market without increasing costs. The critical choice is how to regroup components in a module and which physical parameters have to change to differentiate the products (Ulrich and Eppinger, 2000).

Another example can be personal computers where the keyboard, monitor and CPU have different parameters to customize product configurations. Another example is mentioned in Dahmus *et al.* (2001), where coffee-makers and tea-makers share the same modules like the heating system. The choice of the common module saves costs and respects the specifications of two different products. Another example is the software applications where program codes are developed in different modules where development groups work on different modules of codes. Meyer and Lehnerd (1997) also gives other examples of the use of modules and platforms on industry.

3. Overview of some methods

This section mentions some interesting works to define modules and platforms to develop products. The applications cover different domains and dimensions of manufacturing engineering. For a general first view of modular methodologies on product development the reader can refer to Fixson (2001) and Joines and Culberth (1996). The Table 2 is a classification of the literature of this chapter.

3.1. *Modular methods*

Several modular methodologies can be appreciated in the concept "Group Technology". This principle can be summarized as follows: if several problems are similar then one solution can be found if they are grouped. Usually the application of "Group Technology" is to regroup manufacturing operations. The basic algorithms in group technology are: (1) MADROC (Chandrasekharan and Rajagopalan, 1986), (2) Production Flow Analysis (Burbidge, 1982) (3) Single Linkage Clustering (McAuley, 1972) (4) Rank Order Clustering (King and Nakornchai, 1982), (5) Bond Energy Algorithm (McCormick *et al.*, 1972), (6) Numerical Taxonomy (Carrie, 1973).

There exist other methods for grouping or distinguishing modules for example:

- Clustering methods (like the group technology basic algorithms).
- Graph and matrix partitioning methods (Huang and Kusiak, 1998). Kumar and Chandrasekharan (1990) give a summary of matrix partitioning methods.
- Mathematical programming methods: an interesting work searching modules of production process by linear programming is in

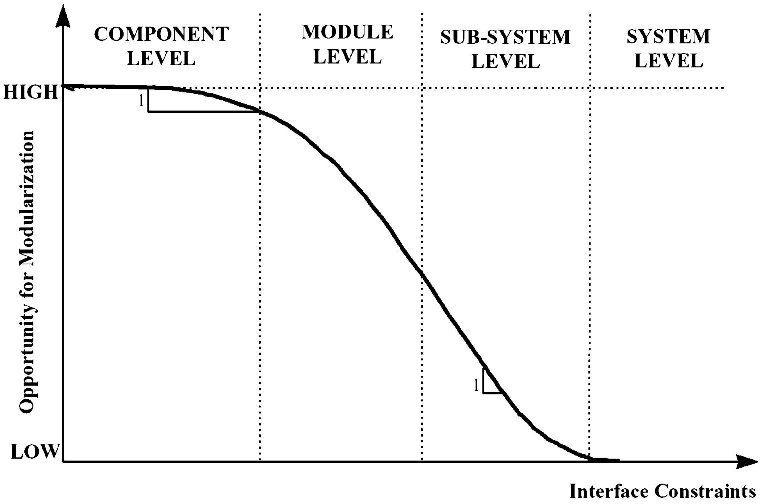


Fig. 9. The system level of design dictates the level of interface constraints and opportunity to modularity (Mikkola, 1999).

Table 2. These works can be classified as: methods (step by step), mathematical tools, algorithms (to find an optimized design)

References	*Method*	*Mathematical (Tool)*	*Algoritm*	*Conception*	*Représentation*	*Evaluation of Modularity*	*Postponement or manufacturing approach*
Agard (2002)			M	M			M
Bongulielmi *et al.* (2001)	A				M, A		
Burbidge (1982)			M				M
Carrie (1973)			M				M
Chakrabarti (2001)		M				A	
Chambolle (1999)	A				A		
Chandrasekharan and Rajagopalan (1986)			M				M
Dahmus *et al.* (2001)	M, A			M	A		
David and Kusiak (1998)			M	M	A		M
Dobrescu and Reich (2001)			P	P	P		
Evans (1963)		M		M			
Fellini and Papalambros (2000)	P			P	P		
Gonzalez-Zugasti and Otto (2000)			P	P	P		
Hadj-Hamou (2002)	M, A			M, A	M, A		
Hata and Kimura (2001)		M		M		M	
Huang and Kusiak (1998)	M		M	M	A	M	
Jianxin and Tseng (1999)	M, P	P		P	M		
King and Nakornchai (1982)			M				M
Kumar and Chandrasekharan (1990)					M	M	
Kusiak (1987)			M	M			
Kusiak (1999)	M, A		M, A	M, A	M, A		
Kusiak and Larson (1995)	A				M, A		
Kusiak and Wang (1995)			M, P	M	M	M	M, P
Lee and Tang (1997)		P		P			P
Martin and Ishii (1997)		A		A			A, P
McCormick *et al.* (1972)			M				M
Meyer and Lehnerd (1997)	P	P		P		P	
Mikkola and Gassmann (2001)		M				M	
Nayak *et al.* (2000)			P	P			
Otto (2000)			P	P			
Otto (2001)	M			M			
Otto *et al.* (2001)	M			P	M		
Pedersen *et al.* (2001)			P	P	P		
Robertson and Ulrich (1998)	P			P			
Simpson *et al.* (1996)			P	P			

Table 2. Continued.

Swaminathan and et al. (1998)			P		P
Swaminathan and et al. (1999)			P		P
Thomas (1991)			M	M	
Venkat and Rahul (2002)	P			P	
Viriththamulla (1991)		M, P	M, P	M, P	

Applications are oriented to: (1) product architecture, (2) modules, (3) platforms. The dimensions are: product conception, representation of systems, tools to evaluate the degree of modularity, orientations to manufacturing. Some references are part of 2 or more axels. *A* – Product Architecture Orineted; P – Product Platform oriented; M – Modular Construction.

Kusiak (1987). A good classification on modular works on linear programming is in Viriththamulla (1991).
- Artificial intelligence.
- Genetic algorithms and other heuristics.

An example of a modular method is in Otto (2001). He mentions some ways to translate the market requirements in quantified product functions. He develops three heuristics to group these functions in a module to manage variety. He proposes to follow several steps in this sense for example:

- to analyze the needs and product uses of the client
- to identify functions within the family structure
- to cluster functions in relation to heuristics
- to select physical modules, in technological and physical dimensions
- to compare and select product architectures

Dahmus *et al.* (2001) mentions a method following several points:

- Market variance analysis (quantity of segments)
- Usage variance analysis (type of product functionality and possible changes)
- Tendency of the technological changes
- Production, supply and lifecycle considerations, called Design for "X"

Hata and Kimura (2001) use a method to develop modules based on product life cycle rules:

- Don't combine components made with different materials
- Don't combine components with different life time cycle
- Don't combine components with different maintenance intervals

Methods of representation of a modular system

To represent possible combinations of modules some works consider the use of representation models, like Bongulielmi *et al.* (2001), who represent the design and modules of requirements in a matrix to visualize the variety offered. Hadj-Hamou (2002), uses the approaches of UML and STEP to represent a product and possible module configurations. Chambolle (1999) uses a STEP approach to model the system of product components and variety. Kusiak and Larson (1995) use graphs and a matrix to represent three systems: product, problem and process decompositions, with the objective to divide and analyze modular decompositions. We could also mention, between others, the works of David *et al.* (1998), Dobrescu and Reich (2001), Kumar and Chandrasekharan (1990).

Methods in order to measure the efficiency in the construction of modules

Some works mention some methods to *measure modularity* in a design and use efficiency indices. For example, Mikkola and Gassmann (2001) mentions how a product can be easily leveraged to different other products measuring modularity in one of them. She mentions that if a product is highly modular it can be used to design other products. She mentions how to evaluate modularity:

$$M(\mu) = e^{-\mu^2/2N_S\delta}; \quad \delta i = \frac{\sum K_{\mathrm{c}}}{N_{\mathrm{c}}};$$

$$\delta_{\text{average}} = \frac{\sum_{i=1}^{I} \delta i}{I}; \quad S = \frac{\text{No.of product families}}{K_{\mathrm{NTF}}}$$

Where: $M(\mu)$ = Modularity function, μ = Number of NTF (new to firm) components, N = Total number of components, K_{c} = Number of interfaces, I = Number of subsystems, δ = Degree of coupling, N_{c} = Number of components, S = Substitutability factor, $K_{\mathrm{NTF\ (avg)}}$ = Average number of interfaces of new components.

Chakrabarti (2001) mentions an architecture index of the relationships between components as well as their functions to measure a "possible" modular design. Meyer and Lehnerd (1997, Ch. 6) make a study using different modular and platform indexes that measure the quantity of derivative products, costs and time to develop them using a platform. Kumar and Chandrasekharan (1990) mention measures of efficiency by the calculus of the percentage of components in and out of a module.

Hata and Kimura (2001) develop two ways to evaluate a module: (1) percentage of common components based on the life cycle rules. (2) percentage of relationships of components inside the module in relation with outside module component relationships.

Mathematical methods

Huang and Kusiak (1998) use an interesting algorithm to organize product components in modules and to identify differentiation components. They use a matrix. The method allows to identify the number of modules to produce and the number of differentiation components to use in order to satisfy variety. Kusiak (1999, Chs. 2, 3, 11 and 12) mention some interesting algorithms to find:

- modules in the product architecture to produce different products
- groups of standard components and the number of unique product components to produce different products

David *et al.* (1998) developed an algorithm to evaluate the ability of modules to replace others. The method considers the restrictions in terms of functionality in a family of products and the place of the module in the bill of materials and assembly sequence.

Kusiak *et al.* (1995) mention a methodology to find modules of production activities based on a matrix activity–activity. They evaluate the modularity of the matrix with density functions ("density" = number of activities in each module). They find critical operational paths in the production line.

Agard (2002) mentions an algorithm to optimize the partition of a design in modules. He takes into account the saving in time if isolated modules are produced by external suppliers.

Thomas (1991) mentions an algorithm that shows how a group of components can be standardized comparing each component to each other, in order to form standard modules. Several mathematical functions are used to calculate costs of such communalization to form modules.

King (1980) developed one of the first algorithms to form a module which is now part of the array based methods of "Group Technology". He mentions how to group machines inside a cell. He uses a matrix "component-machine".

3.2. *Platform methods*

Meyer and Lehnerd (1997) mention a diagram, exhibited in Fig. 10, as the method to develop a product family with platforms. The method consists of 3 phases:

1. Make the segmentation of the market; identify customer needs and the product performance for each segment. A careful analysis of product functionalities is made in this phase.
2. Study the different platforms which have particular interfaces allowing to adapt the design in an horizontal or vertical manner. See Fig. 11.
3. Make a communality study of each "Building Block Dimension".

Otto *et al.* (2001) mention some methods of module selection for a platform construction based on rules of grouping functions. This work takes the aesthetics characteristics of products to choose modules. They use a matrix to group modules.

Robertson and Ulrich (1998) present 3 phases to support the planning of a platform development:

- Use a product plan (like a pert diagram) which describes the products that the company will offer in the future and the kind of clients which will use the products.
- Make a differentiation plan that describes how the products are going to be different from one to another (by attributes and characteristics).
- Make a communality plan which describes which modules are going to be different and which are going to be standard (common) between the products. They evaluate the cost of such standardization and differentiation.

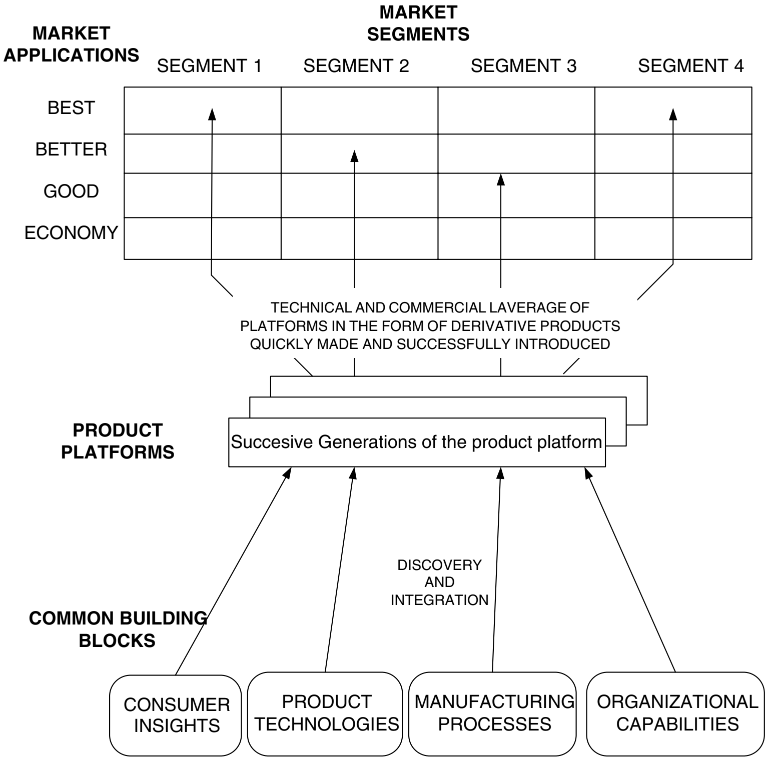


Fig. 10. Meyer and Lehnerd (1997). Three levels of study developing a product family: (1) Evaluation of the market, (2) Evaluation of optimal platform for efficient leverage, (3) Standardization study on different building blocks dimensions.

The modules that permit the differentiation of the product attributes and have low costs are defined as differentiation modules, if not as standard modules.

Venkat and Rahul (2002) use a method of 3 phases to develop products based on a group of standard modules:

- In the first phase they make a functional representation of all products to be able to find modules; this phase refers to "Stone" Module function representation.
- Second, they use a pareto-optimization in the product architecture to find the configuration of modules that permits functionality for each product.
- The third is a technique to refine the design of each product.

Jiao and Tseng (1999) deal with the problem of defining standard modules and finding special modules for product differentiation using an analysis of 3D (functional, technical and physical) on the design of products to develop a unique modular architecture:

- In the functional view they group similar functions in modules, they use a mathematical equation to distinguish attributes belonging to each functional module.
- In the technical view they use a matrix (Design parameters vs. Functions) and use the algorithm of Newcomb *et al.* (1998) to find modules of "functions" in this matrix.
- In the physical view they make an evaluation of physical restrictions and evaluate the acceptance of the module configuration for the products.

Martin and Ishii (1997) expose a method to evaluate the level of common components in a product architecture. They mention how to evaluate the influence of the level of communality in the point of differentiation in the production line (postponement). Several costs are evaluated in this work to calculate the optimal point of differentiation, the number of common components can represent the platform.

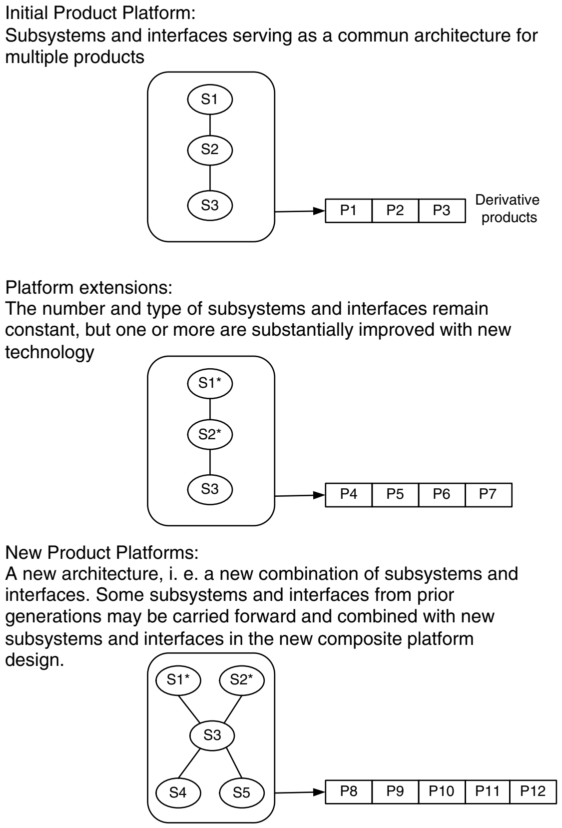


Fig. 11. Horizontal and vertical leverage upgrading the platform (Meyer and Lehnerd, 1997).

3.3. *Platform using mathematical approaches*

Between some algorithms, we could mention for example Otto (2000) who makes a mathematical model minimizing a target function related to the modules needed in each product. The model is subject to family constraints and compatibility constraints between modules.

Fellini *et al.* (2000) use another matrix to group functions in modules; they use a mathematical programming method to generate a platform for each product in the family. The objective is to evaluate all platforms in order to select one platform for the family of products.

Pedersen *et al.* (2001) mention a method to know the level of standardization in the product architecture. The article mentions a numerical taxonomy (like in biological classifications) to classify components in modules according to their evolution. Both algorithms group components of similar attributes in modules.

Swaminathan and Tayur (1998) produced an algorithm which consider a stochastic product demand, he measure the commonality of components between products and economies using Vanilla boxes (or platforms). They use a model of two stages:

(1) Build Vanilla Boxes (V.B.) in terms of module attributes
(2) Choose of the best V.B., for derivative products.

They take into account the restriction of assembly capacity (time), along with the objective of minimizing stock costs vs. stock short-out costs. The results are analyzed measuring the correlation of product demands. A similar work is on Swaminathan and Tayur (1999).

Gonzalez-Zugasti *et al.* (2000) mention a method to form a platform for a defined group of products. Each possible platform configuration is analyzed by mathematical programming and they choose the best scalable parameters. The method measures the adaptability of scalable modules to form a platform.

Nayak *et al.* (2000) mention a method to develop a platform and to find the scalable variables (differentiation components). A scheme of the method is exhibited in Fig. 12: in Stage 1 they use a mathematical programming method called DSP to find a platform and scalable variables for a family of products. In Stage 2 they use an adapted DSP to find individual parameter values. A related work can be found in Simpson *et al.* (1996) they analyze the functionality on each product (of the family). They change the parameters of components to find a common platform and to find differentiation parameters in defined components. The objective is to develop a family of products.

Lee and Tang (1997) present a model that measures different costs factors of the company when it manages a variety of products. These factors are:

1. Design costs.
2. Modular design process.
3. Restructuring costs (re-sequence process operations to allow differentiation).

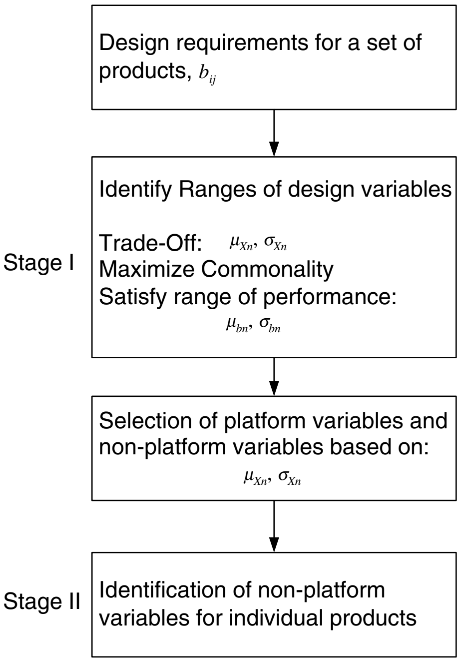


Fig. 12. Two stage method to develop products using a platform (Nayak *et al.*, 2000).

Their objective function minimizes these costs when changing either the point of differentiation in the process or the sequence process. (The point of differentiation in the production line is related to the number of platform components). The model measures the maximum commonality between products and minimizes the costs of production, stocks, set-ups and system complexity, by changing the point of differentiation along the production line. The model uses two algorithms using annealing programming and Branch and Bound.

Dobrescu and Reich (2001) mention the construction of a common platform where each product is made with a *unique platform*. They try to standardize the different product platforms into only one platform. The objective function measures the level of standardization, functionality requirements of each product, number of functions of differentiation components and the physical effort of adapting commonality between components in a 3D space.

Viriththamulla (1991) uses a mathematical programming approach to create different products using the minimum number of modules and components. The model optimizes the number of modules in a product design, minimizing the over and under equipment of components covering each product component requirements. Such study represents a good basis for a platform study.

4. Conclusion and perspectives of research

This paper provides a review of modular design methodologies. An analysis of this literature shows that the efficient design is the one that allows an easy upgrade to develop different products, as well as product life cycle savings. A methodology in this sense should consider an efficient analysis of component parameters to satisfy each product family requirements.

The Platform development allows several advantages, therefore standard and differentiation components should be carefully balanced inside a modular architecture. An analysis of the literature about this aspect allows to observe the interest to maximize the use of common components in the architecture allowing a maximum of distinctiveness between products as shown in Fig. 13. One of the principal interests may be to develop a family of products using a maximum number of standard components which, along with minimal architecture changes, allows to develop different products. In this sense an special objective is to find "less sensible architectures" to the tendencies of the market. In other words, to find which components could be re-used between products in a way to have the flexibility to respond to future market needs.

A perspective of research would be to measure the influence of components in the architecture toward defined product characteristics. Also to analyze the physical restrictions of components like their compatibility, tolerances, interface restrictions, functional restrictions, manufacture compatibility and other factors considering other products life cycle activities in an integral manner. The problem is to represent these factors and the principal variables costs of the industrial context.

Possible works could be made using system representation methods; in this sense STEP models can help us identifying physical platforms and assembly restrictions, design constraints and other product life cycle variables. Another method could be UML models.

Today the methods for platform product development are not practical and future results

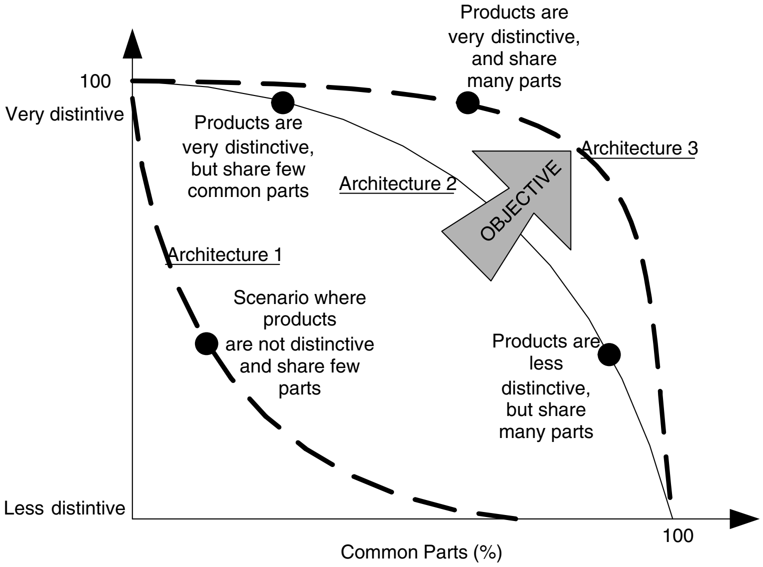


Fig. 13. The trade-off distinctiveness vs. commonality depends on the architecture characteristics. Robertson and Ulrich (1998).

can be obtained with an integral methodology using a practical design representation linked to an optimization methodology. Such methodology should link the most important costs, the economic savings and the design choices.

Notes

1. Mass customization emphasizes the need to provide products that meet customer's needs at a low cost through modular components, (Pine, 1993; Kotha, 1995; Feitzinger and Lee, 1997; Gilmore and Pine, 1997). It allows companies to satisfy special needs which could not be met by standard products.
2. Example, scientific management principles according to standardized work designs and specialization of labor (Taylor, 1967), nearly decomposable systems (Simon, 1996), and (Adam, 1776) view on division of labor and task partitioning.
3. They give an excellent review about modular basics.
4. By economic policies or governmental rules.
5. Take for example a BMW R1100RS Motorcycle. The motor is the power source and structural support of the bike. The classical tubular support structure is not used so the power and support functions in this case would be an independent module (the motor).

References

Adam, S. (1776) *An Inquiry into the Nature and Causes of the Wealth of Nations*, London: W. Strahan and T. Cadell.

Agard, B. (2002) *Contribution à une méthodologie de conception de produits à forte diversité*. Ph.D. Thesis, INPG, Grenoble France.

Baldwin, C. Y. and Clark, K. B. (1997) Managing in the age of modularity. *Harvard Business Review*, (September–October), 84–93.

Baldwin, C. Y. and Clark, K. B. (2000) *Design Rules. Volume 1: The Power of Modularity*, Cambridge, Masseachusetts: MIT Press.

Bongulielmi, L., Henseler, P., Puls, Ch. and Meier, M. (2001) The K- and V-matrix method—an approach in analysis and description of variant products. *International Conference on Engineering Design (ICED) 01 Glasgow*, 21–23 August.

Burbidge, J. L. (1982) The simplification of material flow systems. *International Journal of Production Research*, **20**(3), 339–347.

Carrie, A. S. (1973) Numerical taxonomy applied to group technology and plant layout. *IJPR*, **11**(4), 399–416.

Chakrabarti, A. (2001) Sharing in design—categories, importance, and issues. *International Conference on Engineering Design (ICED) 01 Glasgow*, 21–23 August.

Chambolle, F. (1999) Un modèle produit piloté par les processus d'élaboration. Application au secteur automobile dans l'environnement STEP. Laboratoire ≪Productique Logistique≫. Ph.D. Dissertation, École Centrale Paris.

Chandrasekharan, M. P. and Rajagopalan, R. (1986) Modroc: an extention of rank order clustering for group technology. *IJPR*, **24**(5), 1221–1233.

Corbett, J., Dooner, M., Meleka, J. and Pym, C. (1991) *Design for Manufacturing: Strategies, Principles, and Techniques*, New York: Addison Wesley.

Dahmus, J. B., Gonzalez-Zugasti, J. P. and Otto, K. N. (2001) Modular product architecture. *Design Studies*, **22**(5), 409–424.

David, H., Kusiak, A. and Tseng, T.-L. (1998) Delayed product differentiation: a design and manufacturing perspective. *Computer-Aided Design*, **30**(2), 105–113.

Dobrescu, G. and Reich, Y. (2001) Design of a gradual modular platform and variants for a layout product family. *International Conference on Engineering Design (ICED) 01 Glasgow*, 21–23 August.

Elgård, P. and Miller, T. D. (1998) Defining modules, modularity and modularization, design for integration in manufacturing. *Proceedings of the 13th IPS Research Seminar*, Fuglsoe 1998, ISBN 87-89867-60-2. Aalborg University.

Evans, D. (July-August 1963) Modular design—a special case in nonlinear programming. *Operations Research*, **11**, 637–647.

Feitzinger, E. and Lee, H. L. (1997) Mass customization at Hewlett-Packard: the power of postponement. *Harvard Business Review*, (Jan–Feb), 116–121.

Fellini, R., Papalambros, P. and Weber, T. (2000) Application of a product platform design process to automotive powertrains. *Eighth AIAA/USA/NASA/ISSMO, Simposium on Multidisciplinary Analysis And Optimization*, 6–8 September, 2000, Long Beach, CA.

Fixson, S. K. (2001) Three perspectives on modularity a literature review of a product concept for assembled hardware products. Massachusetts Institute of Technology Engineering Systems Division Working Paper Series ESD-WP-2001-06.

Fujita, K., Sakaguchi, H. and Akagi, S. (1999) Product variety deployment and its optimization under modular architecture and module commonalization.

1999 ASME Design Engineering Technical Conferences, DFM-8923, Las Vegas, Nevada.

Galsworth, G. D. (1994) *Smart, Simple Design*, Essex Junction, Vermont: Oliver.

Garud, R. and Arun, K. (1995) Technological and organizational designs for realizing economies of substitution. *Strategic Management Journal*, **16**(Summer), 93–109.

Gilmore, J. H. and Pine, B. J. (1997) The four faces of mass customization. *Harvard Business Review*, (Jan–Feb), 91–101.

Gonzalez-Zugasti, J. P., Otto, K. and Baker, J. (2000) A method for architecting product platforms. *Research in Engineering Design*, **12**, 61–72.

Hadj-Hamou, K. (2002) Contribution à la conception de produits à forte diversité et de leur chaîne logistique: une approche par contraintes. Thèse de l'Institut National Polytechnique de Toulouse.

Hata, T. and Kimura, F. (2001) *Design of Product Modularity for Life Cycle Management*, Department of precition Engineering, University of Tokio, Hongo, pp. 7–3–1.

Huang, C.-C. and Kusiak, A. (1998) Modularity in design of products and systems. *IEEE Transactions on Systems, Man and Cybernetics, Part-A: Systems and Humans*, **28**(1), 66–77.

Huang, C.-C. and Kusiak, A. (1999) Synthesis of modular mechatronic products: a testability perspective. *IEEE/ASME Translation on Mechanotronics*, **4**(2), 119–132.

Jiao, J. and Tseng, M. (1999) A methodology of developing product family architecture for mass customization. *Journal Of Intellignet Manufacturing*, **10**, 3–20.

Joines, J. and Culberth, C. T. (1996) *Manufacturing cell Design: An Integer Programming Model Employing Genetic Algorithms*, Department of Industrial Engineering, North Carolina Sate University, pp. 27, 695–27, 906.

José, A. and Tollenaere, M. (2004) Using modules and platforms for product family development: design and organizational implications. *Fifth International Conference in Integrated Design and Manufacturing in Mechnaical Engineering (IDMME)*, University of Bath, Bath United Kingdom.

King, J. R. and Nakornchai, V. (1982) Machine-component group formation in group technology: review and extention. *International Journal of Production Research*, **20**(2), 117–133.

King, J. R. (1980) Machine-component grouping in production flow analysis: an aproach using a rank order clustering algorithm. *International Journal of Production Research*, **18**(2), 213–232.

Kotha, S. (1995) Mass customization: implementing the emerging paradigm for competitive advantage. *Strategic Management Journal*, **16**, 21–42.

Kumar, C. S. and Chandrasekharan, M. P. (1990) Group efficacy: a quantitative criterion of goodness of block diagonal forms of binary matrices in group technologie. *International Journal of Production Research*, **28**, 233–244.

Kusiak, A. (1987) The generalized group technology concept. *IJPR*, **25**(4), 561–569.

Kusiak, A. (1999) *Engineering Design: Products, Processes, and Systems*, San Diego, CA: Academic.

Kusiak, A. and Larson, N. (1995) Decomposition and representation methods in mechanical design. *Journal of Mechanical Design, Vol.* **117**(B), June, pp. 17–24.

Kusiak, A., Wang, J., He, D. W. and Feng, C. X. (1995) A structured approach for analysis of design processes. *IEEE Transactions on Components, Packaging, and Manufacturing Technology—Part A*, **18**(3), 664–673.

Lee, H. L. and Tang, C. S. (1997) Modelling the costs and benefits of delayed product differenciation. *Management Science*, **43**(1) 40–53.

Martin, M. and Ishii, K. (1997) Design for variety: development of complexity indices and design charts. *ASME Design Theory and Methodology Conference. September 1997. Sacramento, CA. DETC97-DFM4359. ASMEDTC CD, ISBN 0-7918-1243-X. Presented at the 1997 ASME Conference.*

McAuley, J. (1972) Machine grouping for efficient production. *Production Engineer*, **51**(2), 53–57.

McCormick, W. T., Schweitzer, P. J. Jr. and White, T. W. (1972) Problem decomposition and data reorganization by cluster technique. *Operations Research*, **20**(5), 993–1009(the bond energy algorithm).

Meyer, M. H. and Lehnerd, A. P. (1997) The power of product platforms, building value and cost leadership, New York, The Free Press.

Mikkola, J. H. (1999) Modularization in black-box design: implications for supplier-buyer partnerships. *DRUID Winter Conference*, 7–9 January, Holte, Denmark.

Mikkola, J. H. (2000) Product architecture design: implications for modularization and interface management. *Paperwork presented at LINK Workshop, 15 May, Organizing processes of Learning, Copenhagen Business School, Denmark.*

Mikkola Juliana, (2003), Modularization in New Product Development: Implications for product Architectures, Supply Chain Management, and Industry structures. Ph.D. Thesis, School of Technologies of Managing, Copenhagen Business School, Denmark.

Nayak, R. U., Chen, W. and Simpson, T. W. (2000) A variation-based methodology for product family design. *Proceedings of DETC'00 ASME 2000 Design Engineering Technical Conferences Baltimore*, 10–13 September, Maryland.

Nevins, J. L. and Whitney, D. E. (1989) *Concurrent Design of Products & Processes: A Strategy for the Next Generation in Manufacturing*, New York: McGraw-Hill.

Newcomb, P. J., Bras, B. and Rosen, D. W. (1998) Implications of modularity on product design for the life cycle. *Journal of Mechanical Design, Transactions of the ASME*, **120**(3), 483–491.

Otto, K. (2000) Modular platform-based product family design. *Proceedings of DETC'00 ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference Baltimore*, 10–13 September, 2000, Maryland.

Otto, K. and Sudjianto A. (2001) Modularization to support multiple brand platforms. *Proceedings of DETC: ASME Design Engineering Technical Conferences*. DETC 2001, DTM-21695, September 9–12, Pittsburgh, Pennsylvania, USA.

Otto, K. (2001) Identyfing product family architecture modularity using function and variety heristics. PaperWork Center for Innovation on Product Development, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA.

Pahl, G. and Beitz, W. (1998) Engineering Design A systematic approach, Springer-Verlag, ISBN 0-387-50442-7.

Pedersen, K., Allen, V. and Mistree, F. (2001) Numerical taxonomy—a systematic approach to identifyng potential product platforms. *International Conference on Engineering Design (ICED) 01 Glasgow*, 21–23 August.

Pine, B. J. (1993) *Mass Customization: The New Frontier in Business Competition*, Boston, MA: Harvard Business School Press.

Robertson, D. and Ulrich, K. (1998) Platform product development. Working Paper, The Wharton School, University of Pennysylvania.

Sanchez, R. and Collins, R. P. (2000) *Competing and Learning in Modular Markets*, Elsevier Science Ltd., 3 PII: S002 4-63 01(01)00099–1.

Sanchez, R. and Mahoney, J. T. (1996) Modularity, flexibility, and knowledge management in product and organization design. *Strategic Management Journal*, **17**(Winter Special Issue), 63–76.

Simon, H. A. (1996) *The sciences of the artificial*, 3rd edition, Cambridge, MA: MIT Press.

Simpson, T. W., Maier, J. and Mistree, F. (2001) Product platform design: method and application. *Research in Engineering Design*, **13**, 2–22.

Simpson, T. W., Chen, W., Allen, J. K. and Mistree, F. (1996) *Conceptual Design of a Family of Products Through the Use of the Robust Concept Exploration Method*, Vol. 2, 4–6 September, AIAA-96-4161-CP, Bellevue, WA, pp. 1535–1545.

Star, M. K. (1965) Modular Production—A New Concept. *Harvard Business Review*, **43**(November–December), 131–142.

Stone, R. B., Kristin, L. W. and Richard, H. C. (1998) A Heuristic Method to Identify Modules from a Functional Description of a Product. ASME Design Engineering Technical Conferences, Atlanta, GA, ASME, DETC98/DTM-5642, 11.

Swaminathan, J. M. and Tayur, S. R. (1998) Managing broader product lines through delayed differentiation using vanilla boxes. *Management Science*, **44**, S161–S172.

Swaminathan, J. M. and Tayur, S. R. (1999) Managing design of assembly sequences for product lines that delay product differentiation. *IIE Transactions*, **31**, 1015–1026.

Taylor, F. W. (1967) *Principles of Scientific Management*, New York: Norton.

Thomas, L. D. (1991) Commonality analysis using clustering methods. *Operations Research*, **39**(4), 677–680.

Thomke, S. H. and Reinertsen, D. (1998) Agile product development: managing development flexibility in uncertain environments. *California Management Review*, **41**(1), 8–30.

Thyssen, J. and Hansen, P. K. (2001) Impacts for modularization. *International Conference on Engineering Design (ICED) 01 Glasgow*, 21–23 August.

Ulrich, K. (1995) The role of product architecture in the manufacturing firm. *Research Policy*, **24**, 419–440.

Ulrich, T. K. and Eppinger, S. D. (2000) *Product Design and Development*, 2nd edition, New York: McGraw-Hill, Inc.

Ulrich, K. and Tung, K. (1991) Fundamentals of product modularity, in *Issues in Design/Manufacture Integration 1991*, A. Sharon (ed.), DE 39 ASME Press, New York, pp. 73–79.

Veeralamolmal, P. and Gupta, S. M. (1999) A combinatorial cost-benefit analysis methodology for designing modular electronic products for the environment. *Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment*, 268–273.

Venkat, A. and Rahul, R. (2002) Module-based multiple product design. *IIE Proceedings*, IERC, Sustainable Design Lab Engineering Management Department, University of Missouri-Rolla Rolla, MO-65401.

Viriththamulla, G. (1991) *Mathematical Programming Models and Heuristics for Standard Modular Design Problems*, University of Arizona.

Wilhelm, B. (1997) Platform and modular concepts at volkswagen—their effects on the assembly process. *Transforming Automobile Assembly—Experience in Automation and Work Organization*, K. Shimokawa, U. Juergens and T. Fujimoto (eds), Springer, Berlin, p. 146.

Zamirowski, E. J. and Otto, K. N. (1999) *Product Portfolio Architecture Definition and Selection, ICED 99 Munich*, 24–26 August.