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Systematic design of SME manufacturing and assembly systems based on Axiomatic Design

Philipp Holzner[a]*, Erwin Rauch[a], Pasquale Russo Spena[a] and Dominik T. Matt[ab]

[a]*Faculty of Science and Technology, Free University of Bozen-Bolzano, Piazza Università 5, Bolzano, 39100 Italy*
[b]*Fraunhofer Italia Research s.c.a.r.l., Innovation Engineering Center (IEC), Schlachthofstrasse 57, Bolzano, 39100 Bozen Italy*

* Corresponding author. Tel.: +39-0471-017111; fax: +39 0471 017009. *E-mail address:* philipp.holzner@unibz.it

Abstract

To produce a high-quality product at the lowest possible price as quickly as possible, is certainly one of the biggest challenges of a manufacturing organization. In addition, supplier constraints and changes in the law for example makes it necessary for these enterprises to adapt continuously their manufacturing and assembly operations. The customization of products is increasing, and at same time, concepts of series and mass production are declining. This motivate large enterprises but also small and medium-sized enterprises (SMEs) to apply concepts of flexible and agile manufacturing and assembly systems to remain competitive and to react quickly to market changes and consumers' preferences. The aim of this research is to develop a systematically design approach for such systems focusing on SME requirements which were carried out by a questionnaire survey of a sample of several manufacturing SMEs in Italy. Based on the survey results, Customer Attributes (CAs) are identified and then translated in Functional Requirements (FRs). Subsequently these FRs will be deduced into generally applicable Design Parameters (DPs) for supporting the design of flexible and changeable manufacturing and assembly systems for SMEs and to apply finally these design guidelines in a case study.

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1. Introduction

Nearly 58% of the total turnover in Italy is produce by SMEs (including micro enterprises) [1]. This demonstrate the huge potential of these types of companies for the Italian economy.

However, the increasingly of the market dynamics due to shorter innovation cycles and unpredictable forecasts is the current situation in which these manufacturing organizations are operating. To remain competitive there production must have a high degree of flexibility and changeability. At this regard, the conceptual design and realization of flexible and agile manufacturing and assembly systems have had a notable impact on many manufacturing enterprises over the last ten years and have also been object in research [2-6].

The hypothesis of this research is also, that this SME oriented countries, like Italy, might be more productive and efficient using more flexible and changeable manufacturing and assembly systems.

The research, whose based on a research project, aims to investigate design guidelines for the design of SME oriented flexible and changeable manufacturing and assembly systems through the Axiomatic Design and to apply these design guidelines afterwards in a case study. The information necessary to start with the Axiomatic Design were obtained from a survey, which was carried out during the research project. The survey based on a questionnaire combined with interviews at several manufacturing SMEs in the province of Bolzano (North of Italy).

2. Literature Review

In many studies and researches the difference between flexibility and changeability types are considered at an

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aggregate level or they fail to provide operational definitions of manufacturing and assembly flexibility and changeability [7]. The types and dimensions of manufacturing and assembly flexibility and changeability considered for this work are describe in this chapter.

2.1. Flexibility and changeability in Manufacturing

In this work the types of flexibility and changeability are based on a combination of the manufacturing types as proposed in [8-9]. These authors have attempted to provide operational definitions of a wide set of manufacturing flexibility and changeability types. The main difference between flexibility and changeability is that flexibility only permits a system change in a specific corridor. Changeability however describes the responsiveness over the existing flexibility corridor and requires usually a longer time for reaction [10].

In this sense flexibility describes the ability of a production system to change a manufacturing system very quickly, with little effort and therefore with low costs. Predefined sets of measures define changes of possible reachable system states, limited by certain flexibility corridors in the planning phase [11]. By flexibility it is possible, within a defined flexibility corridor, to adjust the manufacturing system. Flexible manufacturing systems allow the change of parts of production systems for the production of new products, which have similarity to the already known product families [12].

In this study, the authors distinguished seven types of flexible manufacturing and assembly systems [13-15]:

1. Variant flexibility: Ability of manufacturing / assembling multiple versions of a product.
2. Quantity flexibility: Ability of adaptation of production systems to fluctuating sales volumes.
3. Technology flexibility: Ability to use the manufacturing and assembly system for a variety of technologies.
4. Successor flexibility: Ability to use for future products also existing equipment or parts.
5. External flexibility: Ability of changing the system by changing components (example robot gripper).
6. Internal flexibility: Ability of changing the system without modifications (example change of internal NC program).
7. Personnel deployment flexibility: Ability to work with a variable number of employees and different worker skills.

Changeability however is the ability of switching from one product family to another and making the appropriate changes in the product capacity of a company or production system. A change can have important impact on the production and logistics systems and also on the equipment structure as well as on the organizational or operational structure. Such a change requires a longer lead-time for planning and takes place relatively quickly [16]. In a more recent work of Wiendahl et al. [4] changeability is defined as characteristics to accomplish early and foresighted adjustments of the factory's structures and processes on all levels to change impulses economically. The authors define the term flexibility as the ability of a system to change its behaviour without changing its configuration.

2.2. Drivers and enablers of changeability

To reach changeability in companies and manufacturing systems, five enablers (see Fig. 2) can be found in the literature [17].

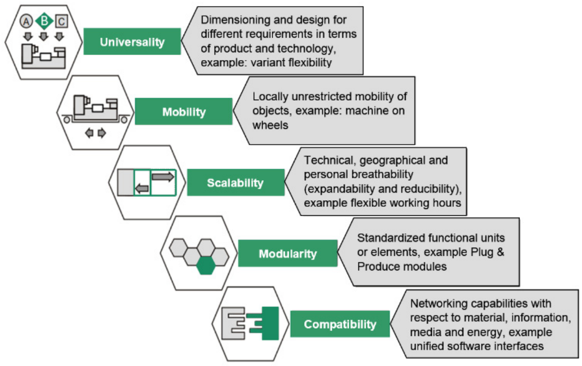

Fig. 1. Enablers of changeability [17].

In addition to these enablers, there are also other enablers not treated in this work such as adaptability towards the customers [18-20].

2.3. Flexible and changeable manufacturing systems for SMEs

Especially for SMEs, costs and flexibility in a production system are very important issues because the products are generally produced in small batches [21-22]. In addition to a high percentage of manual production, this kind of enterprises used mainly universal machines to guarantee a certain flexibility. But also SMEs which have a high degree of automation and manufacture in large batches have to address their production more flexible and changeable to react quickly to market changes and consumers' preferences. In this area, there is still a great need for research [23]. SMEs with a robust and highly flexible manufacturing system have usually a greater market share, a better financial condition and a better sustainable technology [24].

3. AD-based and SME-oriented design of flexible and changeable manufacturing and assembly systems

The research is based on a research project to develop design guidelines for flexible and changeable manufacturing and assembly systems in SME. The research project started with a survey based on a questionnaire combined with interviews at SME companies in the North of Italy. The interviews were conducted with the management or production manager of the participating firms. In total a number of 27 SMEs contributed to the study. Based on the survey results was conducted afterwards an Axiomatic Design investigation to derive design guidelines for the design of SME oriented flexible and changeable manufacturing and assembly systems. The Axiomatic Design analysis was structured in the following steps [25]:

- Identification of Customer Attributes (CAs).
- Transfer of customer needs into Functional Requirements (FRs) at the highest level.
- Assignment (“mapping”) of Design Parameters (DP) to Functional Requirements (FRs).
- Decomposition (“Zig-Zagging”) into several hierarchical levels (top-down) to move from nonconcrete requirements to concrete design parameters (hierarchical FR-DP tree)
- Elaboration and continuous revision of the design matrix
- Application of design guidelines at practical case studies.

3.1. Introduction in Axiomatic Design

Axiomatic Design (AD) was developed by Nam P. Suh in the mid-1970s in the pursuit of developing a scientific, generalized, codified, and systematic procedure for design. At the beginning the methodology was used mainly for product development processes, while AD nowadays has become a commonly used method for the design of products, organizations, manufacturing systems as well as software architecture. The methodology gains its name from two axioms in Axiomatic Design that have to be respected: 1) the Independence Axiom in order to reduce the coupling of the system (avoiding dependencies between the DPs and other FRs), 2) the Information Axiom for the selection of solution alternatives (choose always the “simplest” solution with the least information content).

3.2. Investigation and determination of Customer Attributes (CAs)

The AD-based approach starts with the identification of customer needs. In manufacturing customer needs can be interpreted with needs of manufacturing enterprises facing actual or future challenges on the market. In the mentioned survey the participating SMEs were asked about future challenges and changes in their business environment. The answers in this survey question contributed in this research through a better understanding of customer needs for the design of future SME-Manufacturing.

Therefore principal Customer Attributes for future SME-Manufacturing could be deduced from the survey:

CA1 Handle an increased variety of individual products (Increasing variety and Individualization)
CA2 Being competitive in price and costs (Price competition in the market)
CA3 Handle increasing quality requirements (Increasing quality requirements)
CA4 Deliver products in shortest time (Increasing demand on delivery)

As shown above, 1) Changeability, 2) Price, 2) Quality and 4) Time are the key objectives for SME manufacturing companies. In a next step these CAs needed to be translated into functional requirements and design parameters for manufacturing system design.

3.3. Translation of Functional Requirements (FR) into Design Parameters (DP) and top-down decomposition process

The identified CAs were translated into further first level Functional Requirements (FRs) showing the technical and practical requests for SME-manufacturing system design.

FR1 Increase flexibility and changeability
FR2 Produce at lowest costs
FR3 Improve quality
FR4 Reduce lead time.

Corresponding Design Parameters (DPs) to meet these Functional Requirements were defined as follows:

DP1 Flexible and changeable manufacturing/assembly system
DP2 Low cost manufacturing systems
DP3 Zero defects and TQM in production
DP4 Pull principle and “0” WIP.

FRs and DPs are defined in AD mathematically as a vector. The Design Matrix [DM] describes the relationship between FRs and DPs in a mathematical equation [26]:

$$\{FR\} = [DM]\{DP\} \quad (1)$$

The design matrix on the first hierarchical level shows the relationship of the identified solutions (DPs) on the derived Functional Requirements (FRs):

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \end{Bmatrix} \quad (2)$$

The design matrix shows an uncoupled design. This means that FRs are distinguishable from each other.

This research focuses on the design of flexible and changeable SME Manufacturing and Assembly Systems (MAS). Therefore, based on the related survey results, FR1 and DP1 were further decomposed in additional Axiomatic design levels.

Following, the decomposition process on the next hierarchy levels continues with mapping and “Zig-Zagging”. The Functional Requirement FR1 (Design of flexible and changeable MAS) can be subdivided into further two general FRs (see Tab. 1).

Table 1. Decomposition FR1 - level 2.

FR_{11}	Increase flexibility of MAS	DP_{11}	Flexible MAS
FR_{12}	Increase changeability of MAS	DP_{12}	Changeable MAS

The design matrix shows a decoupled matrix. Changeable MAS are usually flexible at the same time, while a flexible MAS doesn’t have to be changeable.

$$\begin{Bmatrix} FR11 \\ FR12 \end{Bmatrix} = \begin{bmatrix} X & X \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \end{Bmatrix} \quad (3)$$

DP11 and DP12 are very general and abstract design solutions. Therefore it needs a further decomposition in a next level to break down DP11 and DP12 into more concrete proposals for solutions (see Tab. 2 for decomposition of FR11 and Tab. 3 for decomposition of FR12). These further decomposition was executed based on the survey results at SMEs regarding the perceived relevance of types of flexibility and enablers for changeability (see fig. 2).

Types of flexibility	very important	important	less important	not important
Variant flexibility	63%	33%	4%	0%
Technology flexibility	59%	19%	15%	7%
Internal flexibility	44%	26%	7%	22%
Personnel deployment flexibility	37%	52%	7%	4%
Quantity flexibility	26%	48%	22%	4%
Successor flexibility	22%	30%	44%	4%
External flexibility	7%	22%	44%	26%
Enablers for the changeability	**very important**	**important**	**less important**	**not important**
Universality	70%	15%	0%	15%
Reconfigurability	52%	30%	11%	7%
Effort for reconfigurability	44%	41%	4%	11%
Compatibility	26%	48%	15%	11%
Scalability	22%	48%	26%	4%
Modularity	11%	19%	30%	41%
Mobility	4%	22%	44%	30%

Fig. 2. Survey results regarding flexibility and changeability (N=27)

As shown in Fig. 2 "successor flexibility" and "external flexibility" were evaluated as less important and therefore not further considered in the AD decomposition. Also the enablers of changeability "modularity" and "mobility" were assessed as less or not important by the participating SMEs.

In contrast, all very important and important types of flexibility and enablers for changeability have been used for a further decomposition of FR11/DP11 and FR12/DP12.

Table 2. Decomposition FR11 - level 3.

FR_{111}	Produce different products on the same MAS	DP_{111}	Product and variant flexibility
FR_{112}	Possibility to integrate/use different technologies	DP_{112}	Technology flexibility
FR_{113}	Worker can be employed on different work stations	DP_{113}	Staff flexibility
FR_{114}	Quantity can be increased or reduced	DP_{114}	Quantity flexibility
FR_{115}	No need for changeover for changing products	DP_{115}	Internal flexibility

The design matrix of FR-DP in Tab. 2 shows in part a coupled and decoupled matrix.

$$\begin{Bmatrix} FR111 \\ FR112 \\ FR113 \\ FR114 \\ FR115 \end{Bmatrix} = \begin{bmatrix} X & X & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & 0 & X & X & 0 \\ 0 & 0 & X & X & 0 \\ X & X & X & 0 & X \end{bmatrix} \begin{Bmatrix} DP111 \\ DP112 \\ DP113 \\ DP114 \\ DP115 \end{Bmatrix} \quad (4)$$

DP111 and DP112 are in a direct relation to each other. Due to this coupled design a manufacturing system designer should define the level of technology flexibility in relation to the needed product and variants flexibility. To create an optimized design FR111/DP111 and FR112/DP112 should be consolidated to one FR/DP and treated as one work package. Same with FR113/DP113 and FR114/DP114 because staff flexibility has got a big impact on the quantity flexibility of a manufacturing and assembly system. The realization of internal flexibility (DP115) (e.g. the use of programmable industrial robots) is related to more than one FR, therefore it shows a decoupled design. Due to his decoupled design, DP115 should be treated after a prior definition of DP111-DP114.

Table 3. Decomposition FR12 - level 3

FR_{121}	Universal application of MAS	DP_{121}	Universality of MAS
FR_{122}	Extensibility of MAS	DP_{122}	Scalability of MAS
FR_{123}	Possibility to adapt MAS	DP_{123}	Reconfigurability of MAS
FR_{124}	Low effort for adaptation	DP_{124}	Quick changeover
FR_{125}	Simple linking of MAS	DP_{125}	Compatibility of MAS

The design matrix shows in part a coupled design.

$$\begin{Bmatrix} FR121 \\ FR122 \\ FR123 \\ FR124 \\ FR125 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & X & X \\ 0 & 0 & X & X & X \\ 0 & 0 & X & X & X \end{bmatrix} \begin{Bmatrix} DP121 \\ DP122 \\ DP123 \\ DP124 \\ DP125 \end{Bmatrix} \quad (5)$$

DP123, DP124 and DP125 are also in a direct relation to each other. All three DPs have the aim to allow a quick adaptation of the manufacturing and assembly system. An adaptation means first the general possibility to adapt the system (DP123). A next aspect is the ability to reconfigure it as quick as possible (DP124) where compatibility between single stations is important (DP125). Due to this close relationship and the coupled design this three steps should be aggregated to a single FR and DP in manufacturing and assembly system design.

3.4. Design Matrix in Acclaro DFSS

Fig. 3 shows the design matrix of the revised decomposition and mapping process. In this work, the software Acclaro DFSS V5.3 of Axiomatic Design Solutions Inc. was used to create the design matrix, to analyze the dependencies between FRs and DPs and to optimize the design. This specific software for Axiomatic Design investigation allows a digitally assisted review and check of the independence axiom. In addition the software includes different views of the AD-analysis such as FR-DP decomposition, the design matrix or a visualization of FR-DP dependencies in form of a tree-diagram.

As seen in the decomposition process a coupled design (full matrix with circular reference) shows a not ideal design. Therefore the designer has to redefine/redesign the FRs and DPs or to consolidate coupled FR-DP to a single work package. If we have to deal with a decoupled design (triangular matrix and path-dependent “good” or useful design) we have to follow a certain sequence in the DPs.

	DP0: SME-Manufacturing System	DP1: Flexible and changeable manufact	DP1.1: Flexible manufacturing/asser	DP1.1.1: Product and technology	DP1.1.2: Quantity and staff flexit	DP1.1.3: Internal flexibility	DP1.2: Changeable manufacturing/a	DP1.2.1: Universality of MAS	DP1.2.2: Scalable MAS	DP1.2.3: Reconfigurability of MA	DP2: Low cost manufacturing systems	DP3: Zero defects and TQM in productic	DP4: Pull principle and "0" WIP
FR0: SME Manufacturing requirements	X												
FR1: Increase flexibility and changeability		X									O	O	O
FR1.1: Increase flexibility			X				X	O	O	O	O	O	O
FR1.1.1: Produce different products with				X	O	O	O	X	O	O	O	O	O
FR1.1.2: Quantity can be varied and work				O	X	O	O	O	X	O	O	O	O
FR1.1.3: No need for changeover for char				X	O	X	O	X	O	X	O	O	O
FR1.2: Increase changeability			O	O	O	O	X				O	O	O
FR1.2.1: Universal application of MAS			O	X	O	O		X	O	O	O	O	O
FR1.2.2: Extensibility of MAS			O	O	X	O		O	X	O	O	O	O
FR1.2.3: Allow a quick adaptation of MAS			O	O	O	X		O	O	X	O	O	O
FR2: Produce at lowest costs		O	O	O	O	O	O	O	O	O	X	O	O
FR3: Improve quality standards		O	O	O	O	O	O	O	O	O	O	X	O
FR4: Reduce lead time		O	O	O	O	O	O	O	O	O	O	O	X

Fig. 3. Revised design matrix in Acclaro DFSS V5.3.

3.5. Application of AD design guidelines in an exemplary case study

Within the survey interviews, the research team collected also suggestions from participating SMEs for testing the application of the elaborated design guidelines. In the following one of the suggested situations will be analyzed and redesigned exemplarily.

The firm in this case study is a small sized company in the north of Italy with 25 persons employed. The firm started in 1995 as a small crafts enterprise processing solid surface material for bathroom furnishings, kitchens and modern interior design. In course of time the firm focused his activity on the production of exclusive bathroom furnishings in solid surfaces. The company produces different types of furnishings for bathrooms: a) wash basins, b) shower trays and c) bath tubs. The production of bath tubs is a highly specialized production process, while the production of shower trays and wash basins – even if they are completely different products – need similar manufacturing and assembly steps. Today shower trays and wash basins are produced on different assembly tables and go from milling/gluing to a next work station for grinding. The aim of the AD-application in this case study was to develop a concept for an innovative und universal manufacturing and assembly system for different types and dimensions of shower trays and wash basins.

Fig. 4 illustrates the result of the conceptual design, based on the AD guidelines from Fig. 3. The figures shows a proposal for a new universal assembly table. The deduced AD-guidelines for product/technology flexibility (DP1.1.1) and for universality (DP1.2.1) are fulfilled by creating a universal assembly table combining different technologies and assembly/finishing steps. Instead of a process-oriented assembly it was developed an object-oriented assembly bringing together the processes and technologies for gluing the different components, for milling and for surface finishing by grinding. The system allows a flexible positioning and fixation of different products (shower trays and wash basins) – therefore every assembly table is able to produce product from both product families.

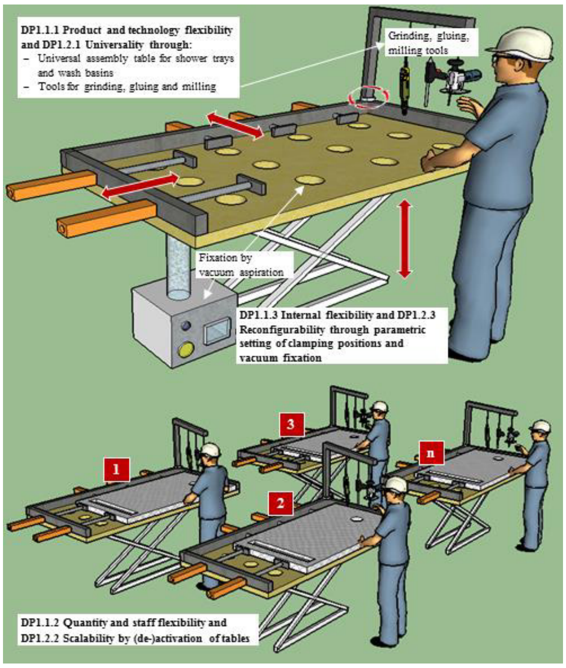

Fig. 4. Case study application: design of a universal assembly table.

The request for internal flexibility (DP1.1.3) in sense of no need for changeover to change from one product to the other can be guaranteed through a parametric setting of clamping positions by the use of movable clamping pistons and a programmable memory function for often-produced products. In addition, a vacuum aspiration supports the fixation of the products on the table. Thus, the system can be reconfigured easily and very quickly (DP1.2.3).

Another AD-guideline is scalability (DP1.2.2). The production starts with a single table producing only small quantities. If the demand increases or decreases, scalability can be achieved by activation or de-activation of additional universal assembly tables in production. In this manner, the quantity can be varied in a flexible way (DP1.1.2) without any need for long changeovers. A prerequisite of such a production principle is a high flexibility of the employed staff. Workers have to be highly qualified because they do not have to assemble one single product type, but varying variants and products on the same assembly table. In addition, workers have to be flexible in their working time. If the SME has got many orders assembly tables have to be active, if there are only few orders the assembly tables have to be deactivated and employees need to be flexible to leave work or to do another work activity.

4. Summary and outlook

Small and medium sized enterprises (SME) represent very often the backbone of countries economy. Therefore this kind of enterprises are also very discussed in research developing specific approaches or concepts in manufacturing. This paper focuses its research actions on the design of flexible and changeable manufacturing and assembly systems in SMEs. Through a questionnaire survey combined with interviews at SMEs the major challenges for the future and the relevance of flexibility as well as changeability in their manufacturing and assembly processes could be identified by the research team. Based in the methodology of Axiomatic Design the inputs from the survey were translated into customer needs and functional requirements to deduce in a systematical top-down decomposition process design parameters for the design of flexible and changeable manufacturing and assembly systems.

With the software Acclaro DFSS V5.3 of Axiomatic Design Solutions Inc. was create a revised design matrix, to analyze the dependencies between FRs and DPs. Finally, the design guidelines were used in a case study and the Axiomatic Design proved to be a purposeful method to find out a suitable solution to find out a flexible and changeable manufacturing and assembly system for a SME. In a next step the identified, and in this research paper described, design parameters will be further decomposed into more concrete and design solutions and design guidelines, in other words by breaking down the DPs elaborated into more DPs.

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