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Technological Modularity in Manufacturing Industries: A Review

[1] Anil Kumar Mahawar, [2] Dr.Vasdev Malhotra
[1] Research Fellow, [2] Associate Professor
[1][2] Department of Mechanical Engineering YMCA University of Science &Technology Faridabad, Haryana

***Abstract*— The idea of modularity has gained acceptance because of so-called mass customization and the need for shorter development time in manufacturing. Modularity is a general concept, and many engineering problems can be generalized under the umbrella of modularity. Numerous studies have been carried out on modularity-relevant issues; however, systematic classification has not been discussed for modularity in terms of its applications and methodologies for developing modularity in systems. This paper presents taxonomy on modularity applications, research issues, and design methodologies. It provides a general framework for further systematic development of modularity in systems. General solutions to identified problems which should be studied in future are also discussed.**

***Index Terms*— Design methodology; Modular design; Modularity; Modularity application;**

I. INTRODUCTION

Quick changes of customers' requirements are the theme of today's manufacturing environment. Many companies are being faced with the problem of providing as much variety of the products as possible for the market, while at the same time keeping as little variety as possible between the products in order to maintain economies of scale. The problems of time to-market and product variety have been discussed in both industries and academia. The origins of the problem are the globalization of the market place and the explosion of product variety. Dynamic changes of the current environment increase greatly the complexity of manufacturing systems. Therefore, the key point for most of the current enterprises is to improve their flexibility rapidly to meet the rapid changes of the dynamic environment.

Flexibility can be achieved in two general ways:

1. To make the components or organizations contain many internal dynamic parameters. In manufacturing industries, this applies to advanced manufacturing systems, such as robotic systems and flexible manufacturing systems. The fundamental idea of these systems is that the system flexibility can be built by changing parameters in planning, scheduling, and controlling the programs.
2. To organize or modularize system components, and to provide the variants by employing different modules and/or different connections among them. The implementation of the external dynamic parameters has implied the requirement for modular architecture of the system at the hardware level. This means that system topology can be changed by removing or adding modules, so, the range of tasks to be fulfilled increases to an "infinite" amount. A typical example is modular robotic systems. Theoretically, the addition of modules (joint and link) can produce various types of robot mechanisms.

II. LITERATURE REVIEW

This paper focuses on modular systems for manufacturing applications. Many new concepts, such as computer-integrated manufacturing (CIM), concurrent engineering (CE), agile manufacturing (AM), global manufacturing (GM), and virtual enterprise (VE) are proposed in manufacturing. All these concepts depend on a suitable physical and information architecture for manufacturing systems. Increasing the modularity of systematic components is a strategy to develop such an architecture. Many workers have discussed the relationships between the modularity and these concepts [4]. The term "modularity" indicates a high degree of independence among individual elements, excellent general usability, and seamless interfacing between elements. Moreover, separate element groups can be assembled into a hierarchical system, and the system can also be decomposed into the original element groups. The characteristics of modularity methodology are generalized as follows:-

Use the finite set of components to meet the infinite changes of the environment. Establish the module by reviewing the

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similarities among the components. Keep as much independence of the resulting cells as possible. Use different modules for different varieties of assemblies. There are many benefits of, and reasons for, modularity. Erixon [5] has identified twelve different reasons, which are called module drivers. These drivers are divided into categories largely according to the product life cycle, product development and design, variance, production, quality, purchasing, and after sales. The potential benefits of modularity include these [6].

- Economies of scale.
- Increased feasibility of product/components change.
- Increased product variety.
- Reduced lead time.
- Decoupling tasks.
- Increase productivity.

The ease of product upgrade, maintenance, repair, and disposal. The objective of this paper is to provide a general framework within which development of modular technology can be tracked, and this may also provide a reference model for coordinating various studies of modular technology and its applications.

The study is organized as follows.

(i) First, applications of modular technology are classified based on the characteristics of modular components and interfaces.

(ii)Secondly, various issues involved in modular technology are discussed and classified.

(iii)Thirdly, design methodologies used in modular technology are summarized.

III. APPLICATIONS OF MODULAR TECHNOLOGY:-

Modularity is used to describe the use of encapsulated units to meet the dynamic changes being faced by their host system. It aims to identify independent, standardized, or interchangeable units to satisfy a variety of functions [7]. Modularity corresponds to flexibility or changeability. It is an effective mechanism to upgrade and reuse existing functions, modules and assemblies. The concept of modularity can be used in any level and domain of manufacturing systems. The objective of the discussion here is to provide applications of the modularity concept based on the features of components and their connections.

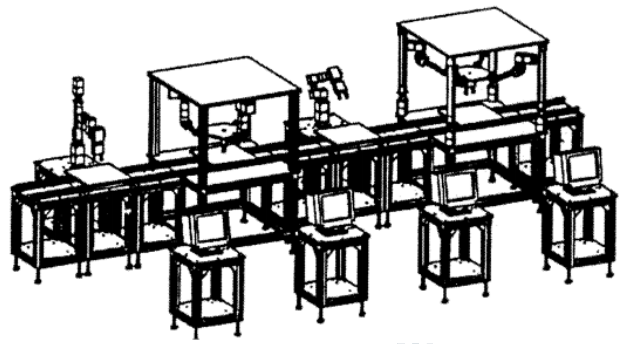

Fig. 1.Architecture of modular robotic work cell

The modular components can be one of three entities: "concept entity", "information entity" or "physical entity". Furthermore, for each type of entity, they can be viewed or integrated in a different level. Regarding the interface among the components, a common classification proposed by Ulirich [8] is used; that is, these interfaces are divided into "component swapping", "components sharing", "fabricate-to-fit" (from the component view point), and "slot architecture", "bus architecture", and "sectional architecture" (from the connection viewpoint). Ulirich's definition is, however, in the sense of a one-to-one interaction at the physical level. In some applications, interactions among components may be made "simultaneously" with more than two entities. Therefore, this paper introduces coordination architecture as one of the interfaces. Figure 1 shows the modular work cell that was developed by Chen et al. [9]. This is a reconfigurable modular manufacturing work cell performing a variety of tasks, such as part assembly, material transfer, and light machining, through a rapid change of reusable work cell components. The work cell hardware is built around modular reconfigurable robot components, such as actuators, links, sensors, end-effectors, and other tools [9].

IV. MODULAR DESIGN

Two basic categories of activities are involved in modular design:-

1. Modularization of a product.(MD-i)
2. Modular configuration. (MD-ii)

4.1 Modularization of a Product(MD-i)

The motivation of modularization of a product is to meet the changing demand for the needs of the product, in particular to achieve maximum flexibility rapidly. The MD-i should result in an architecture of a product such that the product can be made by simply assembling pre-existing components.

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To realize such a modular architecture, product functions, product life cycle issues, and cost should be considered [10].

4.2 Modular Configuration (MD-ii)

Determination of modular configuration is described in [11] as, "Given a set of candidate modules, produce a design that is composed of a subset of the candidate modules and which satisfies both a set of functional requirements and a set of constraints." From this definition, it can be seen that here we assume that a modular architecture of a particular system is ready, and modular components and their interactions are predefined and available. These prescriptions do not mean that interactions between modules are completely fixed. There are still options regarding the interactions. An example of such options can be found from a modular robots where the robotic system consists of link and joint modules, a link module has multiple identical ports which are used as interfaces to connect with joint modules. Figure 2 shows that a prism link module can have several options to connect with two joint modules to formulate an assembly. In fact, the tasks of MD-ii is to work out an optimal assembly by evaluating a set of feasible assemblies [12].

4.3 Issues in MD (i) and MD (ii)

Figure 3 shows the issue in modular design. Issues in MD -i include "identification of requirement", "determination of modular architecture", and "modular design"; while issues in MD-ii include "description of modular architecture and requirement", "determination of sub-problem", "constraints and objectives coordination", and "determination of interfaces and internal variables". Both MD-i and MD-ii involve design evaluation, which can be performed from different points of view: function, flexibility, cost-effect, environment, technique, and complexity. "Design support" is also regarded as a sub activity, which is further divided into "collaborative design", "organization of research and development", and "development of database".

V. MODULAR DESIGN METHODOLOGIES

The design process for MD-i, is an activity, where a modular system architecture is synthesized in the absence of any prior fig. 2. Different assembly options for a prism link module.

(a) A prism link module. (b) Three assembly pattern

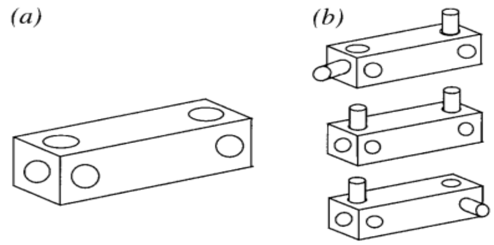

Fig. 2. Different assembly options for a prism link module. (a) A prism link module. (b) Three assembly patterns.

example, while MD-ii, is an analysis activity, where a modular configuration is determined by evaluating a set of feasible configurations. In the following discussion, the axiom design theory (ADT) [13] is applied to develop modular design methodologies.

5.1 Methodologies for MD-i

According to ADT [13], system design involves the continuous processing of information between and within four distinct domains: consumer domain, functional domain, physical domain, and process domain. In fig. 4, it is shown how this theory is applied to the determination of modular architectures.

It is observed that all these methods actually assumed the pre-existence of a product architecture for an existing product. For example, modular robot architecture was developed from conventional robot architectures. It is further found that there is a generic procedure in these tasks. First, components of an existing system are identified. Secondly, criteria are developed which include functions of the product, life cycle issue of the product, and physical interface facility [10]. Examples of the life cycle issues are design for assembly, design for maintenance, design for recycling, etc. Thirdly, some formal procedures are developed to group or cluster the components based on the criteria defined in the second step. At this point, in some way, a score can be assigned on each component, which gives a measure to each component in terms of the criteria. Components with closer scores are then grouped. One of the issues workers have not addressed is how the concepts defined by Ulirich [8] e.g. components sweeping, components sharing, etc. (also mentioned earlier in this paper) are incorporated into this generic procedure.

5.2 Methodologies for MD-ii

In the context of ADT, only two mappings for determining a modular configuration are involved,

1. From customers requirements to functional

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requirements.
2. From functional requirements to design parameters.
In the case of MD-ii, the transformations from design parameters to process variables are simultaneously determined with the mappings 1 and 2. That is to say, once a module is selected, its process parameters are "fixed". At this point, the determination of a modular system configuration differs from the determination of a conventional system configuration where, after the configuration is determined, embodiment and detailed designs will follow with consideration of product life cycle issues, such as manufacturing and assembly. In a sense, life cycle issues for a modular system were considered when its architecture was developed.

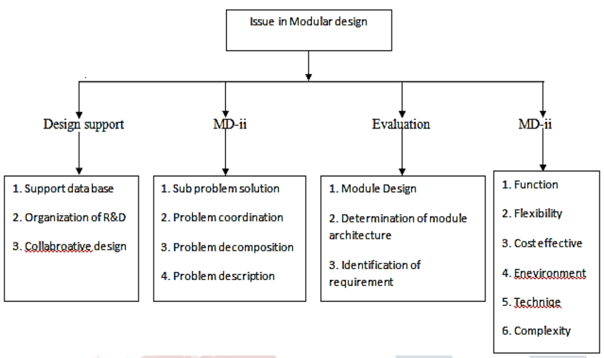

Fig. 3. Issues in modular design.

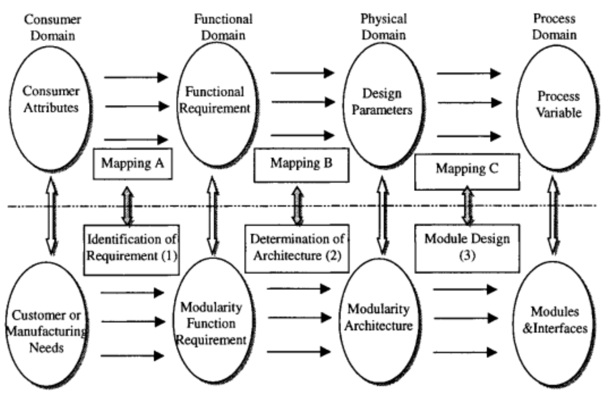

Fig. 4 Relationship between Axiom Design and MD (i).

Determination of a modular system configuration can be treated as an optimizing problem. Existing methods [14] did not take into account the difference between a modular system and a non-modular system. They determined an optimal configuration of a modular robot based on a sequential design procedure, e.g. first, consideration of the kinematic task (for example), and then, of the dynamic task.

We have observed that this sequential design process for the determination of a configuration of a modular system can lead to a situation where, after optimization of the kinematic task, there is no further solution available for tailoring the dynamic task [12]. In this paper, we propose a general strategy based on the ADT for the determination of the configuration of a modular system. It is noted that, for any design, a function-means tree or network can be developed . According to Axiom 1 in the ADT, i.e. the independence principle, when a given modular architecture satisfies the "independence principle", i.e. one physical module satisfies one functional requirement, and the functional decomposition is consistent with the modular architecture, the determination of a modular configuration can be organized hierarchically.

Modular architectures significantly reduce the original continuous/discrete design space into discrete space; on the other hand, they may form strong couplings among design parameters. In the traditional machine design theory, it is known that there are two separate phases: type synthesis and dimensional synthesis. The type synthesis tries to decide whether a cam mechanism or crank-slider linkage should be used for a particular function requirement. The dimensional synthesis is to determine the length of the bar in a crank-slider linkage. Modular architectures of a system appear to diminish the boundaries of type synthesis and dimensional synthesis in the sense that when a particular module is selected for a system, its dimension is fixed as well. For example, in the architecture of a modular robot, a joint is treated as a module with a finite number of types, see fig. 5; furthermore, the connection of any other modular components with the link module could be with a finite number of possibilities, as shown in fig. 2. Such a feature of modular configurations of systems would dispense with the need for methods such as the feature based method [15], modular-based method [16,17], agent-based method [18], entity-based method [19,20], object-oriented method [11,21], case-based method [22], as they are in a sense applicable to the type synthesis of systems. It should be further noted that these methods are essentially constraint oriented and qualitative. On a general note, therefore, a new methodology for the MD-ii, is worthy of study. This new methodology considers simultaneously the functional requirements, in particular to those modular architecture like modular robots.. This will eventually lead to a multiple optimization problem [18].

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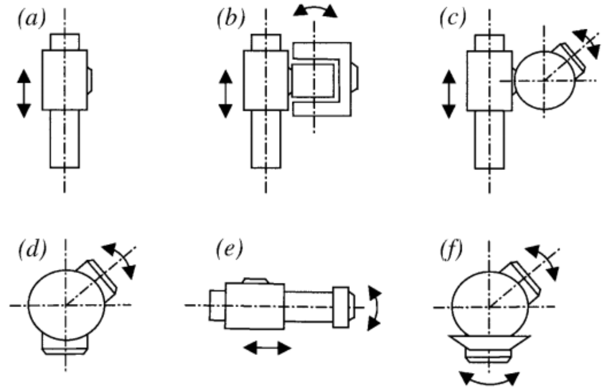

Fig. 5. Some examples of robotic joint modules. (a) Translational joint. (b) Translational and swivel joint. (c) Swivel and translational joint. (d) Swivel joint. (e) Rotary and translational joint. (f) Swivel and rotary joint.

VI. CONCLUSION

Modularity is important in manufacturing, and is extensively discussed in this study. Modularity can be viewed from the following three angles:

1. Its applications (or architectures of practical systems).
2. Its issues.
3. Methodologies for addressing these issues.

They are collectively attributed to a new technology which is called modularity technology. Modular technology for these three angles were discussed in this study. In discussing these new observations were made, salient points of which are highlighted below:

1. A general framework for architectures of modular systems was proposed, with reference to which, architectures of existing modular systems can be analyzed. One of the particular points is the recognition of the so-called coordination concept in this general framework. Further examination of practical usefulness of this architecture is needed.

2. There is a generic computational procedure for developing a modular architecture for an existing system. However, this computational procedure does not appear able to produce a specific modular architecture within the general architecture of modular systems. A preliminary thought would be that the framework components (e.g. component swapping, components sharing, etc.) of the general framework are not on the same level of activities defined in the generic computational procedure. In particular, the activities which would help to produce a specific architecture which contains those framework components may follow activities in the generic computational procedure.

3. Determination of an optimal modular system configuration may need to be modeled as a multiple optimization .Here we take a example of a preliminary study on modular robotic systems[12]. Here the optimization is done by the axiom design theory [13].

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