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Macro level product development using design for modularity

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Abstract

Modular design is an engineering methodology that will organize and structure a complex product, process or system into a set of distinct sub-systems and components that may be developed independently of each other and then assembled together. Modular design aims at identifying independent and standard units that could be used to create a variety of products. A structured methodology is proposed for identifying components that can be developed in parallel. In the proposed methodology the needs and product functional requirements are first established. The product is then decomposed based on its functional and physical characteristics. Next, a similarity index is introduced to measure the associativity between the basic components. Finally, a clustering technique is used to integrate the basic components into design modules based on their similarity index.

1. Introduction

Products are developed to meet some set of specific needs and objectives. Product development process is a sequence of all the required activities that a company must perform to develop, manufacture, and sell a product. These activities contains marketing, research, engineering design, quality assurance, manufacturing, and a whole chain of suppliers and vendors. It also comprises all strategic planning, capital investments, management decisions and tasks necessary to create a new product. An important part of product development is the *engineering design process* that can be defined as the process of devising a system, component, or process to meet desired needs [1]. Engineering design consists of several sequential and/or parallel activities that begin with identifying a need and conclude with a ready-to-manufacture product (Prototype). The prototype is considered to be the first product completed in the production process. The prototype product is produced by using all the manufacturing processes and test procedures specified by the design drawings and specifications. Five major categories associated with the product development methodology have been defined [2]. These are: market-pull, technology-push, platform-products, process based product, customized products, and modular products.

1.1. Market-pull product development

Product development begins with identifying a market opportunity based on customer needs. A market opportunity exists, in product development terminology, when there is a need that can be satisfied by a product of engineering effort. In this approach, the market or the customer performs as the trigger that initiates (pulls) the development of new products in the sense that the voice of the customer is emphasized, and all the development effort is focused on producing a product that is acceptable by the prospective users. Customers or markets provide the requirements that the product must meet. These requirements are analyzed by the design team, and incorporated into the design process. Design specifications and concepts capable of meeting these specifications are also developed according to customer/market requirements.

1.2. Technology-push product development

Organizations begin with a pre-established unique technology and tries to find a market opportunity where this technology can be appropriate. In developing

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successful technology-push products, organizations use basic materials or basic process technologies. This can be referred to the fact that basic materials and basic processes can be deployed in many different applications, which makes it possible to satisfy different market needs.

1.3. Platform products

These products are built around a pre-existing technological system (technological platform). Organizations invest huge capital in developing technological platforms. Therefore, it is well justified that every possible attempt should be made to incorporate these platforms to as many as possible different products. Platform products resemble technology-push products in that both starts with an assumption that a certain technology must be incorporated into the products. Platform products differ from technology-push products in that the platform technology has already proved its ability to meet market needs, and the organization can assume that the technology will be useful in related markets.

1.4. Process-based products

The production process is considered as one of the main constraints placed on the product design. Developing process-based products is usually done for mass production or continuous production.

1.5. Customized products

These products are developed in direct response to customer needs. Customized products are variations of an existing standard configuration of products. To develop customized products, organizations need to set values for design variables such as physical dimensions. These design variables will be changed to meet customer requirements.

1.6. Modular products

Products are designed as building blocks which could be grouped together to form a variety of products. This approach will promote standardization and the re-use of existing modules to develop new products.

2. Modular design

Modular design is a design technique that can be used to develop complex products using similar components [3,4]. Components used in a modular product must have features that enable them to be coupled together to form a complex product. Modular design can be also viewed as the process of producing units that perform discrete functions, then the units are connected together to provide a variety of functions. Modular design emphasizes the minimization of interactions between components, which will enable components to be designed and produced independently from each other. Each component, designed for modularity, is supposed to support one or more function. When components are structured together, to form a product, they will support a larger or general function. This shows the importance of analyzing the product function and decomposing it into sub-functions that can be satisfied by different functional modules.

Modularity can be applied in the product design, design problems, production systems, or all three. It is preferable to use the modular design in all three types at the same time; this can be done by using a modular design process to design modular products and produce them using a modular production system or modular manufacturing processes.

2.1. Modularity in products

Modular products refer to products that fulfill various overall functions through the combination of distinct building blocks or modules [5], in the sense that the overall function, performed by the product, can be divided into sub-functions that can be implemented by different modules or components. An important aspect of modular products is the creation of a basic core unit to which different elements (modules) can be fitted, thus enabling a variety of versions of the same module to be produced. The core should have sufficient capacity to cope with all expected variations in performance and usage.

A good example of modular products is the personal computer (PC). Any PC consists of several components or building blocks such as hard drive, RAM, CPU, CD-ROM, video card, and many other modules. Many modules can be modified or changed with little or no modifications to the other modules. For example, a CPU can be sold with different combinations of hard drives, RAMs, and other options. Through the use of such modular components, a company can choose from a variety of major components and form a product that can meet the customers' needs.

2.2. Modularity in design problems

Most design problems can be broken down into a set of easy to manage simpler sub-problems. Sometimes complex problems are reduced into easier sub-problems, where a small change in the solution of one sub-problem can lead to a change in other sub-problems' solutions. This means that the decomposition has resulted in functionally dependent sub-problems. Modularity focuses on decomposing the overall problem into functionally independent sub-problems, in which interaction or interdependence between sub-problems is minimized. Thus, a change in the solution of one problem may lead to a minor modification in other problems, or it may have no effect on other sub-problems.

2.3. Modularity in production systems

Modularity in production systems aims at building production systems from standardized modular machines. The fact that a wide diversity of production requirements exists has led to the introduction of a variety of production machinery, and a lack of agreement on what the building blocks should be. This means that there are no standards for modular machinery. In order to build a modular production system, production machinery must be classified into functional groups from which a selection of a modular production system can be made to respond to different production requirements. Rogers [6] classified production machinery into four basic groups of "primitive" production elements. These are process machine primitives, motion units, modular fixtures, and configurable control units. It is argued that if a selection is made from these four categories, it will be possible to build a diverse range of efficient, automated and integrated production system.

3. Design for modularity

1. A four-step methodology is introduced for identifying components that can be developed in parallel. The steps associated with methodology include (Fig. 1): (1) needs analysis, (2) requirements analysis, (3) concept analysis, and (4) concept integration.

3.1. Needs analysis

The design engineer is usually given an ill-defined problem. In many situations, the designer has to respond to the mere suggestion that there is a need for a product to perform a certain function. One of the main tasks is to find out precisely what are the needs and what do customers really want. An important step in the design is to describe the product fully in terms of functional needs and physical limitations. These functional needs and physical limitations will form the product specifications.

Several sources of information can be used to identify the needs [7] . Such sources include potential customers, the company for which the design is being made, the competition, and any authorities that can impose restrictions on the product (standards, safety, etc.).

Information required to identify customer needs could be collected by surveying prospective purchasers or customers. This can be done by conducting a marketing study that begins by establishing target markets and customers. Then customers' wants and needs could be obtained by using several methods such as interviews and questionnaires. Also, similar products (competitive products) are investigated to find possible improvement opportunities by focusing on weakness points and desired features by customers. Next, customer wants and needs are arranged into groups and prioritized according to their importance. Needs analysis usually results in a statement of recognized needs and the expected manner in which that need should be met. The resulting information is used to identify the requirements.

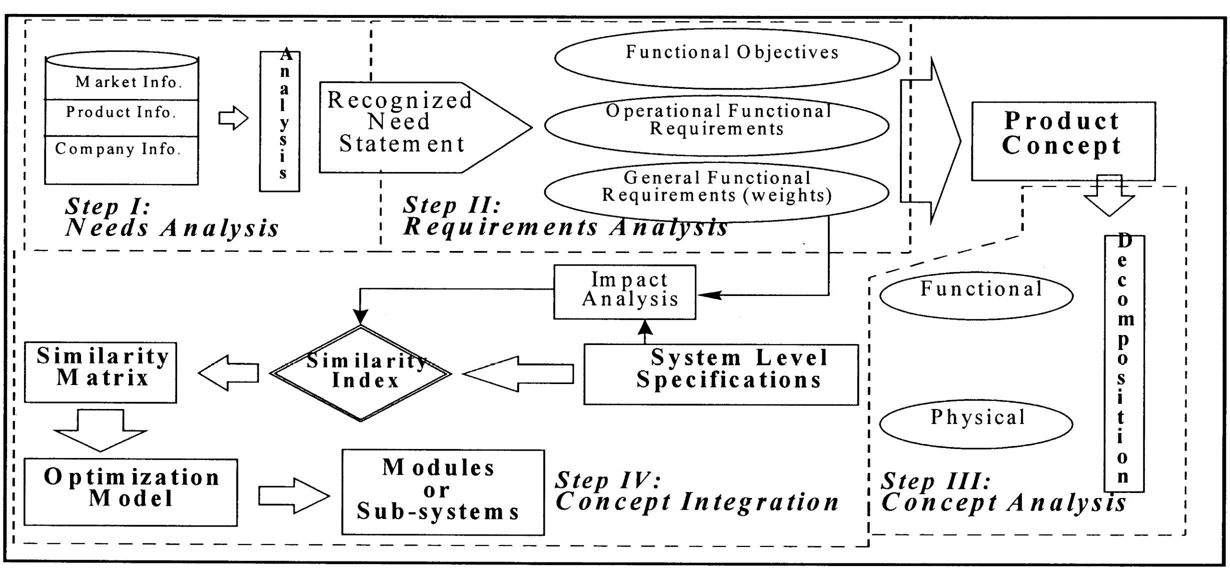

Fig. 1. Design for modularity.

3.2. Product requirements analysis

Results of the need analysis step are used to identify the product requirements. The development group begins by preparing a list of *functional objectives* needed to meet the customer's primary needs. Further analysis of customer needs reveals *operational functional requirements* that impose both functional and physical constraints on the design. Secondary customer requirements will be categorized as *general functional requirements*; they are ranked secondary because they will not affect the main function of the product. That is, a product may lack one or more general functional requirement and still be considered as a functional product that meets the intended function. General functional requirements should be weighted with respect to their importance.

Following is a description of functional objectives, operational functional requirements, general functional requirements, and weights associated with general functional requirements.

3.2.1. Functional objectives

Functional objectives are an abstraction of the product function required to satisfy customer needs. They provide information about what the device/product under investigation is supposed to do. Functional objectives can be thought of as the basic operations or transformations that must be performed by the system to satisfy customers' primary needs. Customers' primary needs are those needs for which the customer will buy the product. Usually customers do not explicitly state these primary needs. Customers assume that these needs are obvious and there is no need to indicate them. For example, the primary need of a car brake system is to stop the car as needed. This need is so clear that most customers may not mention it in an interview. It is the responsibility of the development team to find the primary needs critical to the product usage and translate it into functional objectives. Functional objectives are often somewhat general, but they should always employ action phrases such as "to transform", "to support", or "to lift".

3.2.2. Operational functional requirements

Needs analysis will identify the operational conditions and the physical limitations of the product under investigation, which should be translated into operational functional requirements giving quantitative data wherever possible. Operational functional requirements are detailed and specific information representing a set of constraints that the design must possess in order to satisfy the product intended function. Operational functional requirements could be the result of an integrated effort incorporating marketing staff, design engineers, manufacturing engineers, service personnel, suppliers, and customers. Operational functional requirements are usually presented in the form of ranges. For example, the operational functional requirements of the CPU speed of a computer can be a Pentium 90 MHz to Pentium 166 MHz. Possible operational functional requirements of several products are listed in the following table.

3.2.3. General functional requirements

General functional requirements are the criteria set by the designer, based on the needs analysis, to evaluate the resulting design. General functional requirements are those requirements that satisfy the customers' secondary needs, which could form a critical factor for the customer when comparing different competitive products that accomplish the same function. The general functional requirements will differ based on the prospective markets or users of the product. It can be related to qualitative features of the product such as appearance and color. Also, maintenance needs and assembly could be termed as general requirements. Usually, general functional requirements are stated in general terms.

3.2.4. General functional requirements weights

Several general functional requirements may exist for a product, some are more important than others, therefore different weights should be assigned to different requirements. Customer needs are considered an essential factor in weight assignment. Weight assignment could be made by using a benchmarking study of competitive products. Alternatively, it could be an input of the design team based on previous knowledge of the importance of such requirements.

3.3. Product concept analysis

Product/concept analysis is the decomposition of the product into its basic functional and physical elements. These elements must be capable of achieving the product's functions. Functional elements are defined as the individual operations and transformations that contribute to the overall performance of the product. Physical elements are defined as the parts, components, and subassemblies that ultimately implement the product's function.

Product concept analysis consists of product physical decomposition and product functional decomposition. In product physical decomposition, the product is decomposed into its basic physical components which, when assembled together, will accomplish the product function. Physical decomposition should result in the identification of basic components that must be designed or selected to perform the product function. Product functional decomposition describes the products overall functions and identifies components functions. Also, the interfaces between functional components are identified.

3.3.1. Product physical decomposition

The product is decomposed into sub-systems and/or sub-assemblies capable of achieving the product function. The decomposition process should continue until basic physical components are reached.

3.3.2. Product functional decomposition

Functional decomposition should aim at representing the intended behavior (the functions) of a product and its parts. A function could be implemented by a single physical element (component) or by a combination of elements arranged in a specific manner. Functional components are arranged according to several logical considerations that will ensure the accomplishment of their intended combined function. The logical arrangement is called a working principle [8] which defines the mode of action that the product/system will perform on the inputs to reach the output state. To analyze the product function, the overall function of the product should be conceptualized into an action statement (verb-noun form) [9–12]. Then, the overall function is broken into sub-functions, and those are further decomposed into lower level functions. This function breakdown is continued until a set of functions that could be achieved by available components is reached. At this point functions are mapped into components, and components are arranged forming sub-assemblies leading to an overall assembly that will ultimately accomplish the overall function.

3.4. Product/concept integration

Basic components resulting from the decomposition process should be arranged in modules and integrated into a functional system. The manner by which components are arranged in modules will affect the product design. The resulting modules can be used to structure the development teams needed. Following are the steps associated with product integration.

3.4.1. Identify system level specifications

System level specifications are the one-to-one relationship between components with respect to their functional and physical characteristics. Functional characteristics are a result of the operations and transformations that components perform in order to contribute to the overall performance of the product. Physical characteristics are a result of the components' arrangements, assemblies, and geometry that implement the product function. A general guideline for identifying the relationships can be presented as follows.

(a) *Functional characteristics*
1. Identify the main function(s), based on the functional decomposition.
2. Identify the required operations and transformations that must be performed in order to achieve the function based on the function flow diagram.
3. Document the operations and transformations.
4. Categorize operations and transformations into a hierarchy structure.

(b) *Physical characteristics*
1. Identify any physical constraints imposed on the product based on the requirement analysis.
2. Identify possible arrangements and/or assemblies of the components, based on previous experiences, previous designs, engineering knowledge, or innovative designs/concepts.
3. Document possible arrangements and/or assemblies.
4. Categorize arrangements and assemblies into a hierarchy structure.

Physical and functional characteristics, forming the system level specifications, are arranged into a hierarchy of descriptions that begins by the component at the top level and ends with the detailed descriptions at the bottom level. Bottom level descriptions (detailed descriptions) are used to determine the relationships between components, 1 if the relationship exists and 0 otherwise. This binary relationship between components is arranged in a vector form, "System Level Specifications Vector" (SLSV). Fig. 2 illustrates the hierarchy structure of the physical and functional characteristics.

3.4.2. identify the impact of the system level specifications on the general functional requirements

System level specifications identified in the previous step affects the general functional requirements in the sense that some specifications may help satisfy some general functional requirements, while other specifications might prevent the implementation of some desired general functional requirements. The impact of the SLS on GFR's should be clearly identified which will help in developing products that will meet, up to a satisfactory degree, the general functional requirements stated earlier. The impact will be determined based on,

-1: Negative impact
0: None
$+1$: Positive impact

A negative impact represents an undesired effect on the general functional requirements such as limiting the degree to which the product will meet the general requirement, or preventing the product from implementing the general requirement. While a positive impact represents a desired effect that the SLS will have on the general requirements, such SLS will ensure that the product will satisfy the requirements and result in customer satisfaction. An SLS is said to have no impact if it neither prevents the implementation of the GFR, nor helps satisfying the GFR. An example of the SLS impact on the

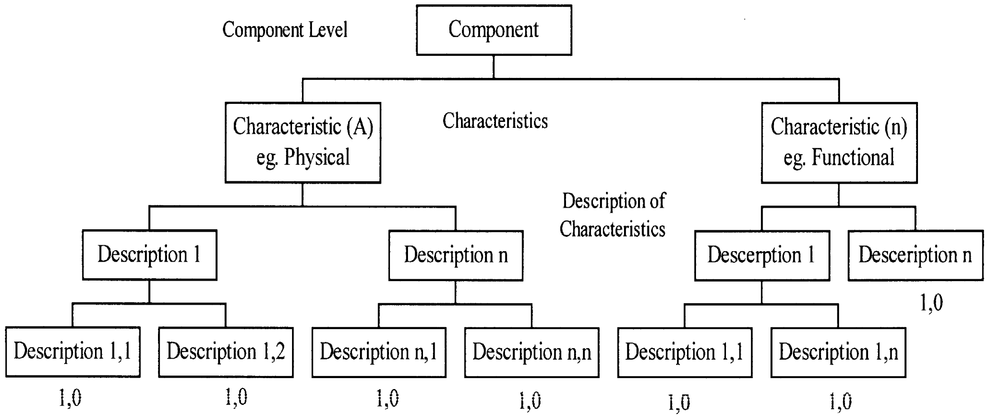

Fig. 2. System level specification decomposition hierarchy.

GFR's is shown in Table 1. For example, the SLS(1) have a negative impact on the FR(1), positive impact on FR(2), and no impact on the FR(m).

3.4.3. Similarity index

The degree of association between components should be measured and used in grouping components into modules. This can be done by incorporating the general functional requirement weights, in addition to the system level specifications vectors and their impacts on the general functional requirements to provide a similarity index between components. The general form of the similarity index is as follows:

$$\begin{array}{ccc} \text{SLSV } (C_1 \,\&\, C_2) & \text{SLS \& FRs} & \text{Weights for FRs} \end{array}$$

$$(S)_{1\times 1} = (1\ 0 \ldots a_n)_{1\times n} \begin{pmatrix} 1 & . & . & . & b_{1,m} \\ 0 & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ b_{n,1} & . & . & . & b_{n,m} \end{pmatrix}_{n\times m} \begin{pmatrix} 1 \\ 0.9 \\ . \\ . \\ c_{m\times 1} \end{pmatrix}_{m\times 1}.$$

The similarity indices associated with components are arranged in a component vs. component matrix as shown below:

$$\begin{array}{c|ccccc|} & C_1 & C_2 & C_3 & \ldots & C_n \\ \hline C_1 & X & S_{1\times 2} & S_{1\times 3} & \ldots & S_{1\times n} \\ C_2 & & X & S_{2\times 3} & \ldots & S_{2\times n} \\ C_3 & & & X & \ldots & S_{3\times n} \\ \vdots & & & & X & \vdots \\ C_n & & & & & X \\ \hline \end{array}$$

3.4.4. Grouping components into modules

Components with high degree of association should be grouped together in design modules. This can be accomplished by using an optimization model that maximizes the sum of the similarities. The optimization model will identify independent modules that can be designed simultaneously. The P-median model [13] will be used to cluster components into modules.

Table 1
GFR vs. SLS

Sys. level specs	General functional requirements		
	FR (1)	FR (2)	FR (m)
SLS (1)	− 1	1	0
SLS (2)	–	–	–
SLS (n)	1	0	1

4. Case study

The proposed design for modularity approach is tested and validated using a test product. The selected test product should possess a moderate complexity to ensure that effort is focused on applying and validating the proposed approach, rather than spent on attempting to understand a complex product. Maintaining moderate complexity will also show the potential for using the proposed approach in designing complex products or systems.

4.1. Problem description

A need to design a speed reducer is identified. The speed reducer is part of the power transmission system of a pump. The power is generated by an electric motor that operates at a fairly high speed while the pump must rotate more slowly. Fig. 3 shows an overview diagram of the system.

4.2. Needs analysis

Following is a list of possible customer needs associated with the usage of the speed reducer.

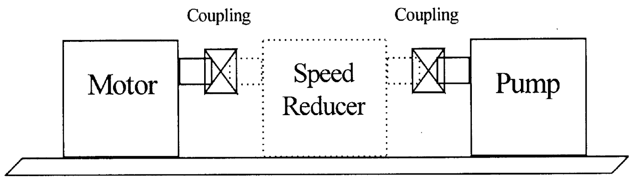

Fig. 3. System diagram.

- 15 hp must be transmitted from the motor to the pump.
- The speed delivered to the pump must be reduced from 2000 rpm (motor speed) to 300 rpm.
- The motor output shaft and the pump input shaft must remain in-line.
- The component of the product should have enough space between them to allow easy maintenance.
- The product should be safe to use.
- The product should be easy to operate.
- The product should use standard materials and components.

4.3. Product requirements analysis

The needs listed in the pervious step are translated into requirements and presented as following:

(a) *Functional objectives*
- To receive power from an electric motor through a rotating shaft.
- To transmit power through machine elements that reduce the rotational speed to a desired value.
- To deliver the power at a lower speed to an output shaft that ultimately drives the pump.

(b) *Operational functional requirements*
- The reducer must transmit 15.0 hp.
- The input is from an electric motor at a rotational speed of 2000 rpm.
- The output delivers the power at a rotational speed range of 290 to 300 rpm.
- The input and output shaft must be in-line.
- The reducer must be installed on a square surface $20'' \times 20''$, with a height of $24''$.

(c) *General functional requirements*
- Performance: The degree to which the design meets or exceeds the design objectives.
- Compactness: Small size and weight.
- Ease of Service: Components should be arranged in a way that it is accessible for maintenance and replacement.

(d) *General functional requirements' weights*
It is assumed that the three general functional requirements listed have equal importance; therefore equal weight of 1's are assigned to all of them.

4.4. Product concept analysis

It is assumed that concept generation and concept selection was performed and resulted in the selection of a four-gear speed reducer to accomplish the required function and meet the requirements stated in the previous step. Fig. 4 shows the selected conceptualized speed reducer.

(a) *Product physical decomposition*
The overall system is decomposed into four physical sub-systems which includes the speed reducer. Then the speed reducer is decomposed into its basic physical components as shown in Fig. 5.

(b) *Product functional decomposition*
The product overall function is conceptualized into an action statement "*To transmit power and reduce speed*", and represented in a function block diagram (Fig. 6).

4.5. Product/concept architecture

4.5.1. System level specifications

System level specifications (SLS) are determined based on the functional and physical decomposition. The resulting decomposition is arranged in a hierarchy structure as in Fig. 7. The one-to-one relationships between components (system level specifications) are determined based on the detailed descriptions of the system level specifications. These are located in the bottom level of the hierarchy. The relationship will be assigned 1 if it exists and 0 otherwise. A partial listing of the resulting system level specifications are listed in Table 2. From Table 2, it can be shown that Gears 1 and 2 have a parallel arrangement and a direct contact. Also, the functional characteristics show that the power is transmitted directly between them and their speed is different.

4.5.2. Impact of the system level specifications (SLS) on the general functional requirements (GFRs)

The impact of SLS on GFRs is determined by using the needs analysis and previous knowledge of the system

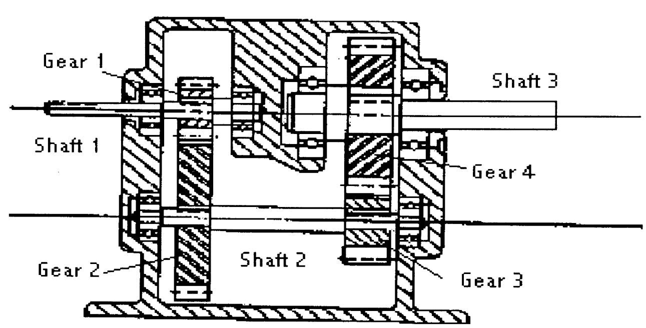

Fig. 4. Four-gear speed reducer.

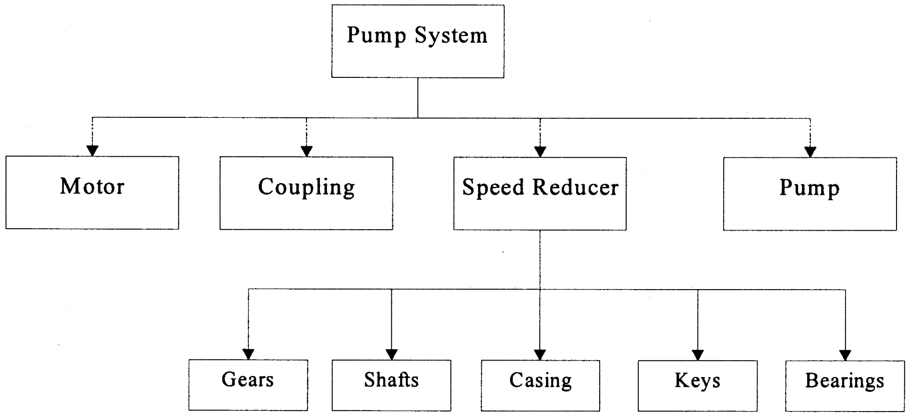

Fig. 5. Physical decomposition of pump system.

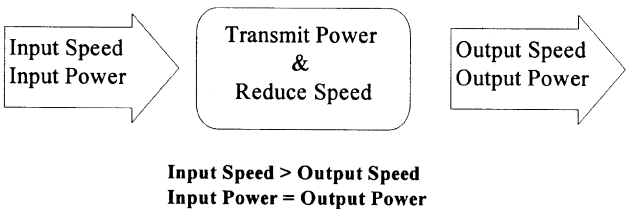

Fig. 6. Overall function of the speed reducer.

under design. In determining the impact, the designer might ask questions such as:

1. What will happen to the GFR if we did/did not have this specific SLS?
2. What kind of effect will this SLS have on the GFR?

Answers to these questions should identify the impacts. If it is a desired impact, it will be assigned (1). If the impact is undesired or if it will prevent the product from achieving its functions, it will be assigned (−1). And if the impact is not significant or it does not affect the GFR, it will be given a (0).

The resulting impacts are shown in Table 3.

4.5.3. Similarity matrix

The similarity index is used to determine the degree of association between the different components. The indexes are arranged in a matrix (Fig. 8).

4.5.4. Grouping components into modules

The p-median model is used to rearrange the similarity matrices into independent modules. The independent modules were found as follows:

1. Construct an optimization model.
2. Solve the model to give two, three, and four independent modules.
3. Compare the results and select the solution that has the maximum objective value.

The best solution had three independent modules as shown in Fig. 9.

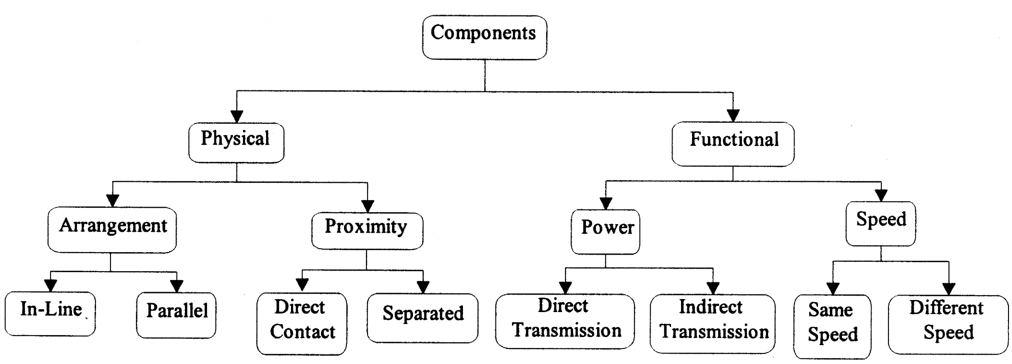

Fig. 7. System level specification hierarchy structure.

Table 2
System level specifications

Comp. 1	Comp. 2	Components							
		Physical				Functional			
		Arrangement		Proximity		Power		Speed	
		In-line	Parallel	Direct contact	Separated	Direct transmission	Indirect transmission	Same speed	Different speed
Gear 1	Gear 2	0	1	1	0	1	0	0	1
	Gear 3	0	1	0	1	0	1	0	1
	Gear 4	1	0	0	1	0	1	0	1
	Shaft 1	1	0	1	0	1	0	1	0
	Shaft 2	0	1	0	1	0	1	0	1
	Shaft 3	1	0	0	1	0	1	0	1
	Bearing 1	1	0	0	1	0	0	1	0
	Bearing 2	1	0	0	1	0	0	1	0
	Bearing 3	0	1	0	1	0	0	0	1
	Bearing 4	0	1	0	1	0	0	0	1
	Bearing 5	1	0	0	1	0	0	0	1
	Bearing 6	1	0	0	1	0	0	0	1
	Key 1	0	1	1	0	1	0	1	0
	Key 2	0	1	0	1	0	1	0	1
	Key 3	0	1	0	1	0	1	0	1
	Key 4	0	1	0	1	0	1	0	1

Table 3
Impact of SLS on GFR

Sys. level specs	General functional requirements		
	Ease of service	Compactness	Performance
In-line	1	1	0
Parallel	1	1	0
Direct contact	0	1	1
Separated	1	− 1	− 1
Direct transmission	0	0	1
Indirect transmission	0	0	0
Same speed	0	0	0
Different speed	0	0	1

The optimization model identified independent modules. These modules could be designed simultaneously. The solution also illustrates that slight interactions do exit between the independent modules. These interactions are represented by the similarity between different components that belong to independent modules. For example, Gears 1 and 2 have a similarity factor of one in the functional modules and a similarity factor of four in the physical modules. This indicates that associativity exists between Gears 1 and 2, that is the design of Gear 1 will affect the design of Gear 2 and vice versa. Although Gears 1 and 2 are associated according to their similarities, they were not grouped in the same module. Which shows that the model used lacks the ability to handle the interaction effectively. These interactions are critical to the development process and must be studied for them.

The association between components belonging to different modules could be used to identify the type of the interactions and thus identify the information required to explain this interaction. For example, Gears 1 and 2 belong to different modules but there exists a functional association between them. This association could be explained by examining the function flow diagram. It can be shown that a major contribution to the function occurred (the speed was reduced). The same can be concluded for Gears 3 and 4.

For physical association, all components were physically interacting with each other. But it can be noticed that components within the same module had a strong association with a major part that will lead the physical arrangement. For example, in module 1, all components had a strong relationship with Shaft 1, which means that the physical location of Shaft 1 will guide the arrangement of the other components. The same can be argued for Shaft 2 in module 2 and Shaft 3 in module 3.

From the above discussion it can be concluded that the design of the speed reducer using the developed modules will be guided by two important interactions: (1) The speed reduction ratio between Gears 1 & 2 and Gears 3 & 4; and (2) The physical location of the three shafts. This includes modules that will be identified based on the speed of the gears and the physical specifications of the shaft.

	Gear1	Gear 2	Gear 3	Gear 4	Shaft 1	Shaft 2	Shaft 3	Bearing 1	Bearing 2	Bearing 3	Bearing 4	Bearing 5	Bearing 6	Key 1	Key 2	Key 3	Key 4
Gear1		5	1	1	6	1	1	2	2	1	1	1	1	6	1	1	1
Gear 2	5		2	1	1	6	1	1	1	2	2	1	1	1	6	3	2
Gear 3	1	2		2	1	6	1	1	1	2	2	1	1	1	1	6	1
Gear 4	1	1	2		1	1	6	1	1	1	1	5	5	1	1	1	6
Shaft 1	6	1	1	1		1	1	5	5	1	1	1	1	6	1	1	1
Shaft 2	1	6	6	1	1		1	1	1	5	5	1	1	1	6	6	1
Shaft 3	1	1	1	6	1	1		1	1	1	1	5	5	1	1	1	6
Bearing 1	2	1	1	1	5	1	1		2	1	1	1	1	2	1	1	1
Bearing 2	2	1	1	1	5	1	1	2		1	1	1	1	2	1	1	1
Bearing 3	1	2	2	1	1	5	1	1	1		2	1	1	1	2	2	1
Bearing 4	1	2	2	1	1	5	1	1	1	2		1	1	1	2	2	1
Bearing 5	1	1	1	5	1	1	5	1	1	1	1		2	1	1	1	2
Bearing 6	1	1	1	5	1	1	5	1	1	1	1	2		1	1	1	2
Key 1	6	1	1	1	6	1	1	2	2	1	1	1	1		1	1	1
Key 2	1	6	1	1	1	6	1	1	1	2	2	1	1	1		2	1
Key 3	1	3	6	1	1	6	1	1	1	2	2	1	1	1	2		1
Key 4	1	2	1	6	1	1	6	1	1	1	1	2	2	1	1	1	

Fig. 8. Similarity matrix.

	Gear1	Shaft 1	Bearing 1	Bearing 2	Key 1	Gear 2	Gear 3	Shaft 2	Bearing 3	Bearing 4	Key 2	Key 3	Gear 4	Shaft 3	Bearing 5	Bearing 6	Key 4
Gear1		6	2	2	6	5	1	1	1	1	1	1	1	1	1	1	1
Shaft 1	6		5	5	6	1	1	1	1	1	1	1	1	1	1	1	1
Bearing 1	2	5		2	2	1	1	1	1	1	1	1	1	1	1	1	1
Bearing 2	2	5	2		2	1	1	1	1	1	1	1	1	1	1	1	1
Key 1	6	6	2	2		1	1	1	1	1	1	1	1	1	1	1	1
Gear 2	5	1	1	1	1		2	6	2	2	6	3	1	1	1	1	2
Gear 3	1	1	1	1	1	2		6	2	2	1	6	2	1	1	1	1
Shaft 2	1	1	1	1	1	6	6		5	5	6	6	1	1	1	1	1
Bearing 3	1	1	1	1	1	2	2	5		2	2	2	1	1	1	1	1
Bearing 4	1	1	1	1	1	2	2	5	2		2	2	1	1	1	1	1
Key 2	1	1	1	1	1	6	1	6	2	2		2	1	1	1	1	1
Key 3	1	1	1	1	1	3	6	6	2	2	2		1	1	1	1	1
Gear 4	1	1	1	1	1	1	2	1	1	1	1	1		6	5	5	6
Shaft 3	1	1	1	1	1	1	1	1	1	1	1	1	6		5	5	6
Bearing 5	1	1	1	1	1	1	1	1	1	1	1	1	5	5		2	2
Bearing 6	1	1	1	1	1	1	1	1	1	1	1	1	5	5	2		2
Key 4	1	1	1	1	1	2	1	1	1	1	1	1	6	6	2	2	

Fig. 9. Independent modules.

5. Conclusions

The major objective of modular design approach is to develop independent and standard components, which could migrate from one product design to another. A systematic approach for modular design was developed offering a product architecture selection based on functional and physical factors.

The developed approach identifies components that could be developed in parallel, which will increase the design efficiency. Also, the approach identifies the interfaces between components in different modules. This can be used to simplify the interactions between components and increase the reusability of the designed components.

The developed approach applies the concepts of systems engineering in which the system is first decomposed into sub-systems and components, and then the components are analyzed and integrated based on their functionality into a functional system capable of achieving the system intended function. The developed approach introduces a parallel development cycle that will reduce the development time, and allow cross-functional team participation.

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