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Modular Clusterization Product Design Support System

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Abstract: Modular design approach is widely used in consumer products, machinery and software design. This article presents the design of a software system to assist designers in clustering modules during product design. Use of scientifically justifiable means of product development which are systematic and less rigorous in a research and development environment leads to reduction in product development time which eventually translates to low cost products. Visual Basic software program, Matlab macros and Microsoft access database were used to come up with an integrated tool which aids in product development. Software modules were linked in such a way as to obtain customer requirements, analyze data by means of a Quality Function Deployment (QFD), cluster parts according to dependencies and give feedback in terms of summarized reports on the different stages of the analysis. This was achieved through the use of a web based application to gather customers' views through an online questionnaire survey and accessed from the company in-house application system for further analysis. The system uses design structure matrix (DSM) as a modular clusterization technique.

Key words: Design Structure Matrix (DSM), Modular Clusterization, Product Design, Product Architecture.

INTRODUCTION

Effective strategies are needed in order to design and develop products that satisfy a wide variety of customer requirements. Research and Development (R&D) departments need to promote commonality, compatibility, standardization, and modularization among different products or product lines. A modular product would mean that the development time is reduced because once the design is split up into modules, design teams can work in parallel on the different modules. The demand for better products is volatile and challenging to manage, the rapid rate of innovation causes short product lifecycles, thus a short production lead time associated with modular products enhances a firm's ability to respond in introducing new products. Modular design approach also promotes re-usability of product modules. With significantly shortened product life cycles, manufacturers have found that they can no longer capture market share and gain higher profits by producing large volumes of a standard product for a mass market. In this era of globalisation and intense competition the long term health of companies is tied to their ability to innovate successfully and rapidly with the customer in mind thus it will be worthwhile to have tools which aid in that direction. The research aim is to come up with a software program which will tap customer requirements, analyze the requirements and interpret them technically, then finally cluster product components according to multi-component relationships. In order to achieve this, there is need for a database model for a research and development (R&D) enterprise which focuses on modular product design approach, a software program with the following software modules: Internet based customer's voice gathering, Quality Function Deployment (QFD) matrix construction, particularly the first phase House of Quality (HOQ1) and product module clustering using the Design Structure Matrix (DSM). The rest of the article looks at the general product architecture, modularization methods, an audit of the case study company to articulate the current problem and lastly develops the system model to aid product research and development.

PRODUCT ARCHITECTURE

A product can be described by both its functional and physical elements. The functional elements are the individual operations and transformations that contribute to the overall performance of the product. The physical elements are the parts, components, and subassemblies that ultimately implement the product's functions [1]. The assignment of the functional elements of a product to the physical building blocks of the product, and definition of the interfaces between the physical building blocks, constitute the product architecture [2]. Four different types of product architecture are identified as follows:

- *Modular design* means that one function is allocated to one module.
- *Function distribution* means that one function is mapped to several modules. This distribution of a function over several modules results in an integrated design at that level.
- *Function sharing* means that several functions are allocated to one module. Again, function sharing increases the level of integration.
- *Integrated design* means that several functions are allocated to several modules. Functions are distributed and shared, thereby further increasing the level of integration

Fig 1 shows the relationship between functions and modules in modular and integrated designs.

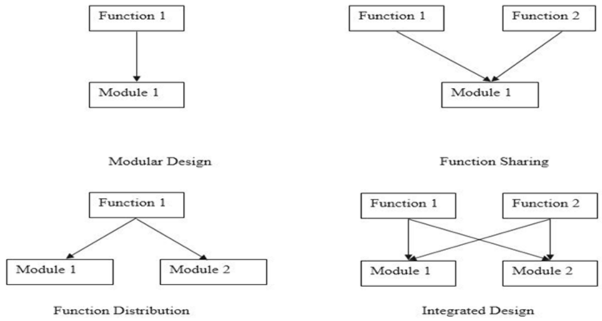

Fig 1: Different types of product architectures [2]

Product Modularization

Product modularization is about grouping a number of components into modules, and defining interfaces between modules. This should be done in such a way that design decisions in one module are isolated from those in other modules. In a modularized product there is loose coupling between the modules; incidental interactions between a module and the rest of the product have been minimized. If this is achieved, the product modularization has the potential to give a number of benefits [3]. Modular product architectures are generated through the application of a pre-defined method. An approach to modularity includes the method by which the architecture is derived. The following steps are followed in coming up with the model that captures the aspects of the product that have implications for the architecture for example where the interfaces are required [4]:

- **Step One**
  This is a view of the requirements of the product. Whatever the source of data, team representatives from Engineering or Marketing functions in the company gather data about the product, its usage, and the customers.
- **Step two**
  Data is analysed to determine what is important in the project. Some data will be discarded at this point, because it is out of scope or does not fit into the representation of the product, be it a matrix, a drawing or a flowchart. What is left may be a list of customer requirements, product properties, desired functions or features, cost data for concept selections.
- **Step three**
  Some choice is typically made about the way this data should be represented. One or several representations may be available, including matrices, flowcharts, and product sketches.
- **Step four**
  If the objective is to make predictions about the best possible modules, it usually becomes necessary to select some type of pre-defined representation. Either a matrix representation which has computer algorithm support for generating modules or a function structure diagram (a type of flowchart) may be used. When diagrams are used, the work may be conducted on paper, and module generation may be manual, using a set of pre-defined heuristic rules for what constitutes good modules. Computer algorithms operating on matrix representations include such methods as Design Structure Matrix (DSM), and Module Function Deployment (MFD).
- **Step five**
  Depending on the algorithm, the output may be a sorted matrix or a dendrogram. The computer-generated output is analyzed by the team members, and decisions are made about modules. Typically, there are many iterations of changing data and resorting before the output is satisfactory. Once the output is deemed useful, it is documented in some form, and goes to detailed design.

Module Clusterization Methods

Six different methods for modularization were identified. The methods are useful for products with simple product architecture that is, one function is allocated to one physical module. However, concerning higher degrees of product complexity, several functions allocated to several physical modules, or large physical variations of the modules, the methods seem insufficient [5]. Table 1 summarises the various methods.

Table 1: Modularization methods

Modularization Method	**Referred to as:**
Fractal product design	FPD
Modular Product Development	MPD
Modelling the Product Modularity	MPM
Modular function deployment	MFD
Design Structure Matrix	DSM
Axiomatic Design	AD

Design Structure Matrix (DSM):
The method includes three steps: decomposition, documentation of interactions between the elements, and finally clustering the elements into chunks [2].

Axiomatic Design (AD):
The axiom that is the basis for the method stipulates that functions in a product should be independent of each other [6]. Two following axioms are used in the method:

• Axiom 1: The independence axiom
• Axiom 2: The information axiom.

The best design is a functionally uncoupled design that has the minimum information content.

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Modular Function Deployment (MFD):

This method contains five steps, and in the description of these steps several tools to be used in the modularization process are given. According to [7] the steps are as follows: (a)- clarifying the customers' requirements, is realized by the use of Quality Function Deployment (QFD). (b)- create sub functions and then find the technical solutions that fulfil these functions. Further, the best technical solution has to be chosen; this selection is done by using a selection matrix. (c)- another matrix called the Module Identification Matrix (MIM) and has the product's sub functions on one axis and the module drivers on the other is used to support the concept generation. (d)- aim at evaluating concepts, and in particular the module interfaces. The aim of this evaluation is to examine if the use of the method has resulted in a modularized product that decreases, for example, the product development costs and time [8]. (e)- improve the module on different levels, e.g., product range, product, and part. Tools such as Activity-Based-Costing and Design-for-Assembly are used.

Modeling the Product Modularity (MPM):

The MPM method uses a different approach for creating the modular structure than the other methods. Matrix algebra is used for structuring both the interactions between the parts in the product, and the suitability of the interactions.

Modular Product Development (MPD):

MPD consists of six steps, and supports the user with guidelines about how each step should be accomplished. It starts with clarifying the task for the product to be designed, and ends with preparing production documents for the product. In detail according to [9] the steps are: (a)- Clarifying the task, (b)- Economic optimization of the modules, (c)- Establishing function structures, (d)- Searching for solution principles and concept variants, (e)- preparing dimensioned layouts and (f)- Preparing production documents.

SYSTEM DEVELOPMENT

A computer based design support system is designed to aid module clusterization in product research and development environment. The system was modeled based on a case study company that manufactures agriculture impliments. Survey results for the case study company are presented first before the system is implemented.

Case Study

The case study company was established in 1949 and since then has been involved in the manufacture of farming implements. The company employs more than 300 people and its products are predominantly marketed in the South of Sahara in Africa. Currently, exports account for 56% of the company's turnover in volume. 51% of the company's raw materials are locally produced while 49% are imported. However, the company enjoys the large market share in the local market. Recently major competition has erupted from China and India. For the past 70 years the company has not had a Research and Development department. Reasons being that:

- The brand has been the monopoly in the manufacture of agricultural implements.
- The needs of the farmer have been assumed to be the same with the ultimate goal of having all basic implements from breaking the soil to harvesting the final crop.
- There has been lack of international benchmarking to analyse global ideas on the same line of business and forecasting the demand of better products in this technology driven market

In an attempt to resuscitate its profits after the realisation of competition the company noted that getting ahead almost invariably hinges on Research and Development. An in house research and development department was introduced in January 2011. Fig 2 shows how sales were affected in 2011 when a company from China suddenly released a batch of its products into the market

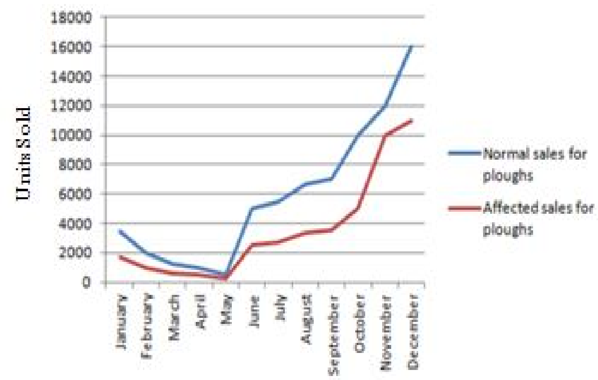

Fig 2: Comparison of sales in the presence of competitors in the year 2011

The company has managed to launch new products in the last ten years with the main aim of staying afloat in business surrounded by competitors. Table 2 shows the trends in new products introduced and their respective launch times.

Table 2: Product introduction and launch times

Period (years)	**Number of products introduced**	**Product name**	**product launch Time (months)**
2003-2005	0	-	-
2006	1	Sheller	19
2007-2008	0	-	-
2009	2	D- Seed planter Ripping plough	18 20
2010	0	-	-
2011	1	P- Planter	24
2012	1	H- Miller	14
2013	1	H- Planter	6

On average it takes about 18 months to launch a new product. From the current Product Development Process (PDP) there is a need to examine it in search of time consuming tasks, redundant operations and unnecessary activities.

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System Model

The system model shows how the system flows as indicated in Fig 3. The following steps explain the system:

a) Questionnaires about a product design project are posted on a web application. Customer needs on the product are also captured via the application. The application is linked to a database and data is sent back to the company server.

b) An in-house analysis is then carried out on the customer needs, this subsequently equips the product development team to complete the customer needs (whats) in the Quality Function deployment module.

c) Product components are then clustered by use of a product module clustering algorithm and the recommended clusters are displayed.

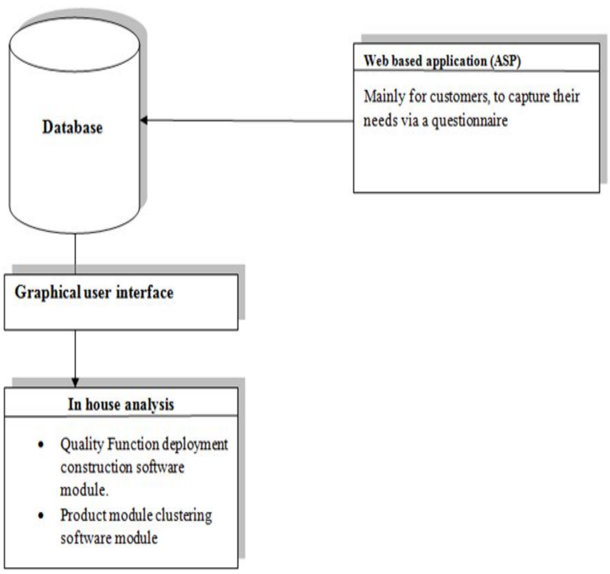

Fig 3: System model

System Use Case Diagram

The main purpose of the use-case diagram is to help development teams to visualize the functional requirements of a system, including the relationship of "actors" (human beings who will interact with the system) to essential processes, as well as the relationships among different use cases.

In the diagram below the two main actors will be:

a) The customer- Has the ability to read and complete the online questionnaire and then submit it. The information will be served in a database in the company server.

b) The employee- Updates the online application from the company premises, posting questions about the product development project. Also responsible for analysing the customer requirements and completing a QFD and then finally using the product module clusterization tool.

Fig 4 shows the use case diagram of the system with the interactions.

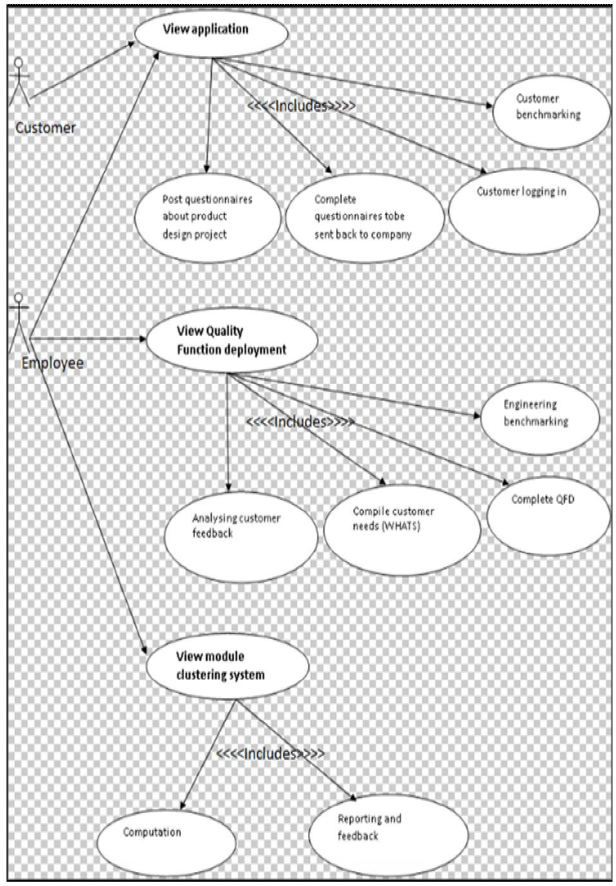

Fig 4: Use-case diagrams for the system

Web Based Application

An Active Server Pages (ASP).Net application which is based on the Microsoft Visual Basic platform was used to create the online customer survey system. The application is hosted on a website. The website will have four pages namely the homepage, Products gallery, customer services and the contact us section. Fig 5 shows the page which leads to the survey and the benchmarking sections.

Fig 5: Customer services page

In-house Analysis System

To access the Research and development projects, users have to log into the system. Once the login is successful, an interface will be displayed which will prompt the user to enter the details of the project and product under development. The processing of information depends on the

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data in the database as per customer requirements; the form which is then called after the search displays three options which constitute the integrated product development tools. The form is shown in Fig 6.

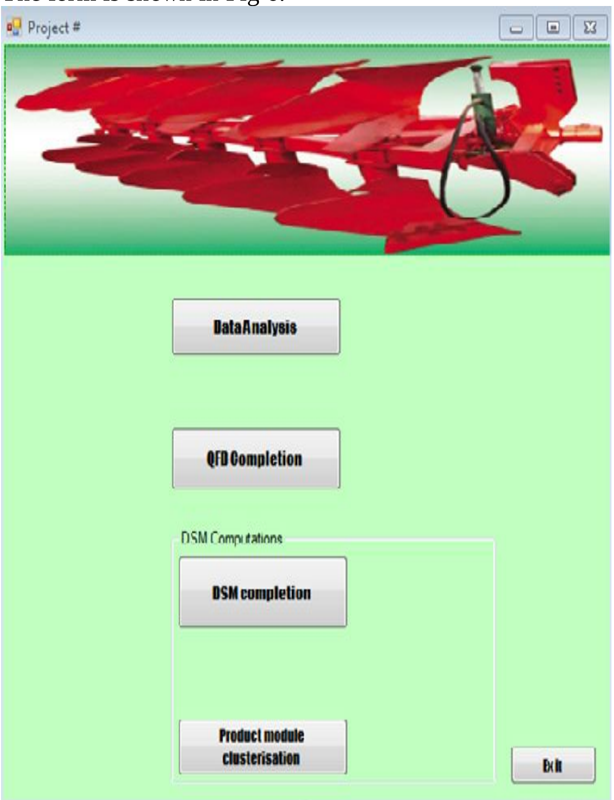

Fig 6: Projects Form for subsequent analysis

Execution of the data analysis command leads to the database where queries can be run on a specific product and in certain fields which contain data under the main requirements criteria; (a) Performance, (b) Usability, (c) Functionality, (d) Safety. The criteria may vary according to the decision of the research and development team. The data is useful for completing the QFD.

Component Clusterization Using Design Structure Matrix (DSM)

DSM component clusterization is executed through the DSM completion command. This leads to a spread sheet based template which generates Matlab code which will continually update an m-file in the current directory of Matlab. DSM creation involves the actual construction of the matrix according to the components of the product under consideration. Information contained in the diagonal and off-diagonal elements is fetched from the main database based on the problem being solved. This includes:

a) The names and intended functions of the components making up the product. The components are automatically counted and entered as the size of the DSM under the Matlab code sheet as the DSM is created. Automatically an array of components is formed on the DSM sheet as shown in Fig 7.

	Components	Adjusting bar holder anc	Axle c/w 2 nuts	Beam	Cross brace	Drawbar assembly	Frog	Handlebar with grip RH	Landside plain	Mouldboard	Regulator	Spreader bar	Handle stay RH	Stay beam to mouldboa	Stay handle to mouldbo	U clamp bolt	U clamp plates	Wheel	Wheel arm	Flat share
Components	1																			
Adjusting bar holder and bolt		1																		
Axle c/w 2 nuts			1																	
Beam				1																
Cross brace					1															
Drawbar assembly						1														
Frog							1													
Handlebar with grip RH								1												
Landside plain									1											
Mouldboard										1										
Regulator											1									
Spreader bar												1								
Handle stay RH													1							
Stay beam to mouldboard														1						
Stay handle to mouldboard															1					
U clamp bolt																1				
U clamp plates																	1			
Wheel																		1		
Wheel arm																			1	
Flat share																				1

Fig 7: Components DSM

b) The relationship between components is then deduced according to standards governing the interaction types as follows;

- 2 - represents a strong interaction (3 or more interaction types)
- 1 - represents a medium interaction (2 interaction types)
- 0.5 - represents a weak interaction (1 or 0)

This is shown by an interaction chart and scoring chart displayed just above the DSM as it is created on the sheet. Fig 8 illustrates the chart.

Type of Interaction	Description
Spatial	Needs for adjacency within two elements
Energy	Needs for enrgy transfer between two elements
Information	Needs for signal or data exchange between two elements
Material	Needs for material exchange between elements
Movement	Translational or rotational
Number of interactions	**Strength of interactions**
2 or more	Strong = 2
Exactly 2	Medium = 1
1 or none	Weak = 0.5

Fig 8: Interaction and scoring chart

c) A script is automatically created which is saved as an m-file in a folder designated as the current directory in Matlab.

The Matlab platform allows computations to be carried out on custom made Design Structure matrix. The software module for the actual clustering of components is developed using Matlab macros that couple a Clustering Algorithm to a Dependency Structure Matrix (DSM) which will then cluster tightly coupled components around the diagonal of the matrix. Computations involve the manipulation of the DSM in terms of performing actual clustering and graphing all in a single command via Matlab macros.

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RESULTS AND DISCUSSION

To evaluate the benefits of the software implementation, a product benchmarking, dissection and components clustering was conducted. This was validated using an existing product to check on the efficiency of the QFD and the DSM software modules. Fig 9 shows the clustered DSM. Tightly coupled components are enclosed in a cluster around the diagonal and the boundary is represented by the blue line.

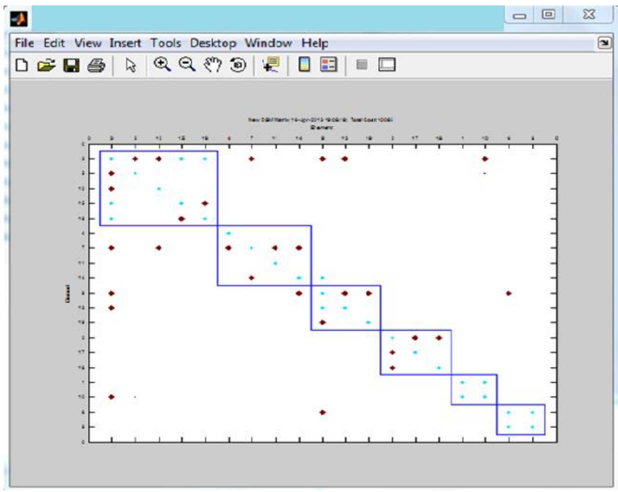

Fig 9: Clustered weighted DSM

Fig 10 serves as a report and feedback display on the details of the clusters listing the names of the elements located in each cluster.

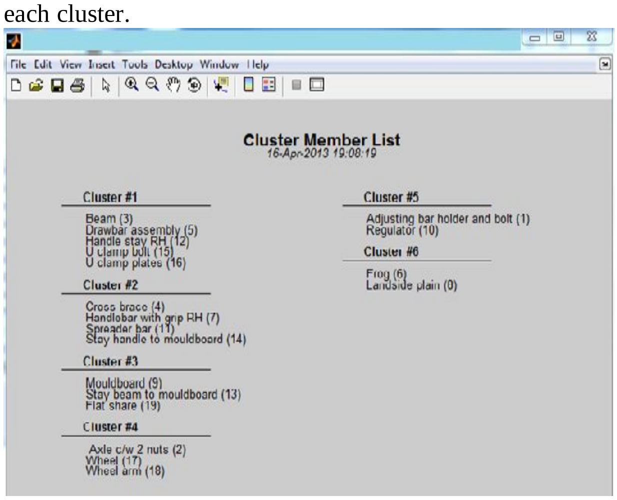

Fig 10: Cluster member list

The clusters represent groups of elements that should have a relatively high level of interactivity. The objective is to maintain interconnections within clusters and to minimise the cross-link between clusters. The clusters can then be grouped together to represent groups that have similar functionality or requirements.

- **Cluster 1**

The cluster represents the main frame work of the plough forming the backbone which can support other components.

- **Cluster 2**

The cluster represents the handling system, that is, the group of components which facilitates holding the plough in position.

- **Cluster 3**

The cluster represents the stronghold of the implement, combining components which are involved in the actual digging of the soil.

- **Cluster 4**

The cluster represents the system which provides motion for the implement to move from one point to another.

- **Cluster 5**

The cluster represents the adjustment system of the plough when conditioning it to work at different depths according to different soil types.

- **Cluster 6**

The cluster represents the support system of the plough.

The solution has facilitated a positive change in the current product development process to achieve improvements in critical measures of performance which include; Cost, Quality, Service and Time-to-Market.

CONCLUSION

The software program provides valuable information that can be used to develop, evaluate and manage the product architecture. Illustrations have been given in result forms and show the feasibility of establishing modular products which have all the qualities required by customers.

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