Extension of the Pahl & Beitz systematic method for conceptual design of a new product

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1. Introduction

Systematic design of a concept of a new product has been dealt with, and was contributed to, by quite a few researchers. A comprehensive method that has been in use for some time has been described in the basic manuscript by Pahl & Beitz [1] (P&B), translated to many languages, serves as basic teaching book that has been improved since. In our studies the method has been extended by introduction of new techniques and tools, that enable to be more specific and more focused. The design methodology is called ICDM – Integrated, Customer Driven, Conceptual Design Method. Three out of the new ICDM tools are shortly described in this paper. These tools are the Enriched QFD for task definition, the CFMA – Conceptual Failure Mode Analysis and the DQM – Design Quality Measurement to evaluate the satisfaction from the generated concepts. The other new tools like the CDTC – the Conceptual Design To Cost, the Robustool – to evaluate and improve the robustness of the solution combination, the RTA – the Risk and Time to Market Analysis and the DSO - the Direct Synthesis Optimization, are only shortly mentioned. ICDM has been used extensively in many Israeli start-up companies and also in classical industrial companies that adapted the method to their special needs.

Systematic Design, ICDM, Conceptual Design, CFMA, DQM

- Enriched EQFD – the enriched Quality Function Deployment for the task clarification. Paragraph 2 summarizes two lessons learned from 15 years of experience in using QFD for task clarification, and the remedies provided by ICDM for these problems.
- DSO – the Direct Synthesis Optimization for the combination step. The step of generating and finding optimal combinations has been considered as a weak point in the P&B design method. A simple way how to overcome this problem, by name of DSO – the Direct Synthesis Optimization has been developed, as a part of ICDM and shown in [8].
- CFMA – the Conceptual Failure Mode Analysis. Paragraph 3 summarizes the principles of CFMA. CFMA [9] modifies the principles of FMEA as described by Stamatis [10] and by other studies, to the requirements and constraints of the conceptual design phase. A very strong design tool.
- DQM – the Design Quality Metrics [17] that estimates the expected quality of the combination. Paragraph 4 describes a new method, based on the results of QFD. The method defined for each product characteristic (PC) a Customer Satisfaction Rating (CSR) function which defines the degree of customer satisfaction according to the value achieved for that PC.
- CDTC – the Conceptual Design To Cost. CDTC [18] helps the product development team to quickly evaluate the major manufacturing costs of the alternative concepts and to reduce cost, when information is still very limited at the very early stages of the design process.
- Robustool – to evaluate and improve the robustness of the solution combination. Robustool [19] is a design tool that provides the prediction of robustness, to select the potentially best concept for a new product, out of the many concepts generated by the use of methodical conceptual design methods, like the ICDM.
- RTA – the Risk and Time to Market Analysis. RTA [20] is a new project planning tool the outputs of which are: identified knowledge gaps, risks analysis and time to market indices to be used in the concept selection phase.

All these design tools were presented and published in the ICED, Design, INCOSE and other journals and conferences. In the current paper only three of these additions to the P&B method, that are included in ICDM, will be highlighted and shortly described. ICDM is now an accepted design tool in quite a few Israeli companies. It fits to design of novel complex products and systems. ICDM has been introduced in many conferences, is a regular graduate course in several Israeli universities and is being taught as special courses inside high-tech companies. It has been implemented in courses in the SEEC and DASI centers in Australia too.
2. The enriched EQFD for task clarification

Quality Function Deployment (QFD) has been used for task clarification for at least 20 years. QFD has a lot to offer but when used to specify a new product, has been found to have a number of deficiencies, has been perceived as a time consuming process and has been found as being difficult to apply to complex systems. The House of Quality is the matrix tool used in QFD to translate the Voice of Customers (VOC) into product characteristics. Product characteristics also known as Measures of Performance are attributes expressed in technical terms as the Voice of Engineering (VOE)) which are used to measure the performance of the product. Examples are range, accuracy, weight, reliability, cost, or time to market. This paragraph summarizes the two lessons learned from 15 years of experience in using QFD for task clarification, and the remedies provided by ICDM for the two following problems:

- QFD is a time consuming process and difficult to apply for complex systems.
- QFD does not support making target value decision tradeoffs for complex systems.

Full details about lessons learnt and remedies provided by ICDM for the task clarification phase can be found in Hari et al. [3, 4].

2.1 Lesson Learnt: QFD is a Time Consuming Process and Difficult to Apply for Complex Systems

One of the problems when using QFD with complex system products and multi-level hierarchical systems consisting of subsystems, assemblies, subassemblies and many parts, is difficult to deal with the many needs of customers and the large number of characteristics (Hari and Zonnenshain, [5]). These problems are caused by the time-consuming nature of QFD. A matrix of more than 20x20 or 15x25 is impractical to handle because it consumes too much time. This makes it difficult for the team to analyze all customers' needs in depth and formulate all correlations and tradeoffs.

Remedy: A Modified House of Quality

The remedy for this situation is to modify the House of Quality as follows:

- 15-20 system level needs (rows), and if necessary also trimmed customer needs hierarchy tree.
- 20 – 25 product characteristics (columns), these being the most important, difficult, or controversial decisions. These are selected in the preparation process for the QFD workshop by the representatives of both the VOC and the VOE. In addition, the House of Quality was modified by adding a column entitled "Other characteristics". This column is a placeholder for the design team to note any product characteristic which contributes to satisfying a need and is not already included in the 20-25 characteristics for discussion.

The QFD literature [6,7] suggests that time be spent quantifying the competitor's ratings and discussing selling points. In the enriched QFD only the name of the competitor who is perceived as being the best in the market in satisfying this need is noted. However, it also seemed worthwhile to present technical information about the competitor's product and the reason for it's perception by the customers as being the best in the market.

The analysis of the correlations among the product characteristics in the roof of the House of Quality is time consuming, and provides little benefit. Instead it was decided to discuss only correlations that actually affect the decision on target values.

The formal output of the modified House of Quality is the ranking of the important product characteristics by relative importance (but all of them are important otherwise they would not be discussed in this stage). But the greatest benefit of the process of populating the enriched House of Quality is the communication and detailed discussion between all the disciplines that are represented in the team and especially between the voice of the customer (VOC) and the voice of the engineering (VOE).

2.2 Lesson Learnt: QFD does not support making target value decision and implication analysis

QFD often does not generate the necessary information needed to make the informed critical decisions required to produce specifications. It is not suited for performing a sensitivity analysis on the consequences of the decisions, it does not incorporate the ability to discuss affordability or "willingness to pay" issues with the customer and does not contain the provision to produce an action-plan and high level verification-plan.

Remedy: The Target Values Decision Table

The remedy for this lack of support developed during the last 15 years of using and modifying QFD, is to add a Target Value Decision Table (TVDT) that contains the quantitative or semi quantitative target values for the most important design characteristics, trade-offs, dependencies and relevant market position of competing products to facilitate decisions that will position the new product relative to the competitors in the market as described below. The TVDT and the process of filling in its data have been considered by most of the team members as 1. the most important part of the process 2. building the consensus 3. the most important modification to the traditional QFD process.

Table 1 is an example of the TVDT for the relevant performance of a typical product namely a flashlight. The TVDT is shown on a screen throughout the decision making process and is populated by the team members. The product characteristics and their relative importance (Weighting) are transferred from the modified House of Quality according to the ranking order the most important one being at the top.

The discussion on each Product Characteristic starts with introduction by the senior VOE representative (usually the system engineer) of the characteristics, the range of debate and possible implications. Then trade-offs against the more important previous decisions are raised, and only the identification number or the name of the conflicting characteristics are noted in the trade off column. The idea behind this is that in case of a conflict between two characteristics, the customer will prefer better performance in the more important characteristics compromising on the less important ones and aiming at the best value that can be achieved.

Then the second (technical) benchmark takes place. The relevant information about the reference products for the decision on each target value is presented here. The best in class is emphasized. Then a short discussion on where this product should be aimed is conducted.

Production of the Target Value column is the formal goal of the entire New Product Definition process. It is where a consensus between the VOC and the VOE should be achieved. This decision sometimes requires deep discussions, bringing into consideration all the information that has been shared and learnt up to this point. Usually this decision is based on the contribution from the various experts who should be represented in the room. Sometimes this column is split into more than one column in
Implication Analyses: After the decision on the target values a discussion on the implication of the target values takes place. These implications are documented in the decision table (see Table 1). The team tailors the implications columns according to their concerns. Some implications are frequently analyzed such as the technical difficulty of achieving the target value, the effect on cost and time to market and the implication on the concept selection. The team uses symbols to present the implication as follows:

- Critical implication, example: the decision on this target value is the prime cost driver of the system cost.
- Important implication, example: the decision on this target value has a significant effect on the time to market but it is not the prime system time to market factor
- Minor implication, example: the decision on this target value involves a minor risk since the same target value has been achieved in a similar system.

One of the issues affecting the target values is the worth of the feature to the customer, namely determining how much money the customer is willing to pay for it.

Action Plan: The target value decision table (see Table 1) includes:

1. tasks required for completion of the decision table,
2. tasks to be performed after completion of the workshop and before completion of the specification document,
3. tasks scheduled for discussion during the requirement review or even
4. tasks for the systems engineer to analyze or to monitor during later design stages.

More details about lessons learnt and remedies provided by ICDM for the task clarification phase can be found in Hari et al. [3,4].

2.3 Conclusions for EQFD

More than 15 years of the application of well-known methods has led to a new task clarification process which:

- Is based on lessons learnt from success and failure cases studies, improvements and modifications
- Has been validated via many workshops.
- Brings to the engineering design process a tried and tested approach for transforming customer's needs to performance based requirements and other attributes of the requirement in the product and process domains that allows the product to be produced more rapidly and correctly than is typically done using other methodologies for developing new products.

3. CFMA – the Conceptual Failure Mode Analysis

After combining the working principles into working structures in step 5 of the P&B conceptual design method, selecting of the suitable combinations out of many that were generated is the next step. Obviously the “best” combinations must be selected, but how can one decide that a certain combination can be considered as part of the “best”? Good potential performance of the new concept as estimated compared to the requirements list is important, but the potential failures of the proposed concept are very important too. The potential performance criteria of the combination are evaluated in this early stage mostly by intuition of an experienced designer. Evaluation of potential failure modes is more complicated, intuition may not be enough, and a quantitative tool is required. The well-known FMEA tool cannot be used in this stage, as most design details are not known yet.

CFMA [9] is a Conceptual Failure Mode Analysis method. It modifies the principles of FMEA as described by Stamatis [10] and by other studies to the requirements and constraints of the conceptual design phase. The essence of the CFMA method is to identify and prevent known and potential failures from reaching the customer. The method is based on teamwork and focused on analysis of potential failures of the system, functions rather than on components, parts and detailed design. The analysis detects the earliest step in the design process when countermeasures can be taken to prevent the failure. Therefore the final product of the method includes design improvements and a list of design and test activities which eliminate the failures and their effects, verify and control the elimination process in the later stages of the design process. Since design details like parts or components are not available at this stage, the analysis cannot be built bottom-up like

| Table 1: Example for Decision Table for the flashlight case study |
| --- |
| **Product Characteristics** | **Trade-offs** | **Ref. Products** | **Target Values** | **Implication** | **References** |
| No. | Units / LIST | W | Charact. | Now | X | Y | Ver. 1 | Diff | $ | TTM | Conceptual | AI | Remarks |
| 1 | Total Volume (cc) | 16% | 022 08 | 57 | 04 | | | | | | | | |
| 2 | Total Weight (grams) | 15% | 022 07 | 09 | 06 | | | | | | | | |
| 3 | Continuous Operation Time (min) | 13% | 04 | 02 | 02 | | | | | | | | |
| 4 | Time to Locate and Operate (sec) | 12% | 01 | 41 | 21 | 8 | | | | | | | |
| 5 | Product Mfg Cost ($) | 12% | 83 82 | 36 1 | 3 1 | | | | | | | |
| 6 | Design Level (scale 1-6) | 10% | 4.5 | 3 | 3 | 2 | 4 | | | | | | |
| 7 | Operations to Failure | 10% | 5 | 005 004 005 | | | | | | | | |
| 8 | Light Intensity (Lux) | 6% | 12 3 6 | 003 003 004 | 002 002 | | | | | | | |
| 9 | Automation Level (List 1) | 4% | 3.4 5 6 | 2 2 | 2 1 | | | | | | | |
| 01 | Time to change batteries (sec) | 5% | 5 | 52 03 06 52 | | | | | | | | |
Application of CFMA is based on a table and on scales of criteria for severity (S), frequency of failure occurrence (F), and detection of failure modes (D). The format of the table and the scales of criteria are modified from various studies but it should be tailored according to the concerns of the design team. Example of a CFMA table and scales of criteria are enclosed. The basic questions that the design team answers during the process are:

1. How can the system fail in performing a function (known or potential) failure modes? (Failure mode column)?
2. What could be the causes and the effects of each failure mode (Failure Cause & Effect columns)?
3. How will the failure effect the customer? (Severity Rating – S column).
4. What is the chance of occurrence of a failure mode? (Frequency Rating - F column)?
5. How can we detect if the potential failure mode does exist in our design, as early as possible in the design process (Detection Method & Detection Rating - D columns)?
6. If the failure mode does exist, how can we prevent it from reaching the customer (Action Items column 7). What is the priority for elimination or minimization of the failure mode? The priority columns SFD and Rev SFD are calculated by the formula: 

\[ SFD = S \times F \times D \]

A part of a typical CFMA table for the design of a new flashlight for the elderly market is depicted in table 4. The Rev SFD is based on the estimated values of S,F, and D after application of the correction action items. The table demonstrates one page of an illustrative example. It analyses the failure modes of the functions “Light an Object” and “Control Operation”. The scales of the parameters S, F and D are shown in the reference. These parameters have to be adapted to the team and the relevant project.

The potential failure modes are often critical for selecting and/or improving concept combinations. In the evaluation of concept variants, the analysis of failure modes is probably the strongest and most influential tool.

### 4. DQM – the Design Quality Measurement

Design Quality Measurement (DQM) has been considered a challenging issue for several decades. Quite a few publications dealt with this issue [11, 12, 13]. The attempt to modify metrics from manufacturing to design generally raises some problems:

- The values of the metrics used for DQM, like percentage of rejects in the production line, number of late engineering changes or time to market, are known generally only after the design process is completed [14].
- When only process metrics are used for DQM (like cost, time to market or number of engineering changes), the team may complete the design of a product which does not satisfy the

### Table 2: CFMA table for the development of a flashlight for the elderly

| Function | Failure Mode | Failure Effect | Failure Cause | Severity (S) | Frequency (F) | Detection Method | Detection Rating (D) | SFD | Action Items | Rev. SFD |
|----------|--------------|----------------|--------------|--------------|--------------|------------------|----------------------|-----|-------------|---------|
| Light an object | Bulb burnt | No light, object not found | Random | 10 | 2 | Eye | 1 | 20 | 1. Add condenser. 2. No spare bulb | 8 |
| | | | Breakage | 1 | 2 | Bulb environmental tests | 2 | 40 | Anti shock restraint for the bulb | 8 |
| | | | Moisture (rain, humidity) | 2 | 2 | Bulb environmental tests | 2 | 40 | Waterproof structure | 8 |
| | | | Tribulations of travel | 4 | 4 | Simulation | 1 | 40 | Restrained structure | 8 |
| Battery weakness | Light too weak | Natural wear of battery | 2 | 4 | 4 | Data from battery supplier | 1 | 8 | 1. Use Alkaline bat. 2. No indication added | 4 |
| | | | Short over battery | 2 | 2 | System environmental tests | 2 | 8 | Plastic structure, isolation | 2 |
| | | | Defective battery | 2 | 2 | Supplier’s data analysis | 1 | 40 | SPC in battery line | 4 |
| Control operation | Switch stuck | Stuck – does not light | Dirt | 10 | 2 | Switch experiment | 2 | 80 | Switch Robust Design | 10 |
| | | | Spring too tight | 2 | 2 | Force analysis | 1 | 20 | Robust Design | 10 |
| | | | Structure twisted | 2 | 2 | Strength analysis | 1 | 20 | Robust Design | 10 |
| | | | Stuck does not stop | 2 | 2 | Force analysis | 1 | 4 | Robust Design | 4 |
customer needs and cannot be sold in the market with perfect grades.

- Repetition and similarity, which characterize manufacturing, rarely exist in design processes which differ from each other significantly by customers’ requirements, product characteristics, complexity, and expertise. Usually it is impossible to construct DQM metrics based on past performance or on standards. We can compare design process data only against forecasts or expectations. These metrics are subjective and subjected to personal influence, power and pressure.

- New product development is a multi-disciplinary process. Use of many metrics, which are required to reflect all the aspects of concern, will create metrics which are not sensitive to some important factors. Selection of a too small number of metrics may not provide good representation of the situation.

- Customer Driven Engineering Design is a process of satisfying the customer’s need by an economic product [15]. The role of the metrics is to measure how the design complies with this definition. Therefore DQM should measure the quality of the product design as well as the quality of the production process and also to comply with criteria of good metrics. Hence, we can define design quality as:

  The value of products of the engineering design process (products, services and processes) as perceived by the internal and external customers versus competitors in the same market. According to this definition one can outline guidelines for definition of DQM metrics in the engineering design process as follows:

4.1 Guidelines for Definition of DQM Metrics

New product development metrics must report the situation to the manager in real time or as soon as possible. They should predict customer satisfaction, innovation, originality, and the product cost. The DQM should provide a balanced set of metrics which highlight the situation, link various activities in the organization and create a quick feedback. The guidelines for definition of DQM metrics are:

1. DQM must be based on the value of the design products as perceived by customer versus competitors [15]. That means considering both, the benefits for the customer, and the total cost of the outcomes of the design process.
2. The metrics must be specific for each project and for each process, otherwise they will be irrelevant, or even encourage unnecessary activities and achievements. They must enable deployment for each product element and for any process, however they should enable integration into general metrics.
3. The metrics should reflect the competitive positioning in the market such as: quality, cost, originality and time to market.
4. The feedback time of the metrics must be as short as possible.
5. Metrics should be available (i.e., already exist in the organization), and be based on reliable data. Metrics should be taken, as much as possible, from basic operational activities of the organization.

4.2 QFD as a Basis for Definition of Metrics for DQM

QFD is a methodology, used for task clarification of new products [7]. During the process the team translates the voice of the customer into the important Product Characteristics (PCs), prioritizes them and agrees upon their Target Values (TVs). This information can create an excellent basis of metrics for DQM. The degree of achievement of the TVs is the best metrics for customers and shareholders satisfaction. Therefore we select the most important PCs as metrics. Since QFD is based on deployment using the principle of cascade, we can deploy each PC into characteristics of assembly, process, control, operation and logistic support [16]. Metrics can be applied for each phase so that the metrics of the entire system are deployed into the important activities of the organization.

4.3 Selection of PCs for Evaluation

Select the most important PCs from the QFD including their measurement units, TVs and relative importance weight. The total importance weight should cover most of the 100% customer satisfaction. PCs can be defined by quantitative parameters like weight, range or cost or by other metrics which enable definitions of the new products in more complex or abstract cases.

4.4 Definition of Customer Satisfaction Rating (CSR) Functions

Define CSR function for each PC selected. CSR function relates the degree of customer satisfaction, to the value achieved at each PC. The team decides together with the customer representatives on the distribution of the CSR function. All the CSR functions must obey the following rules:

1. Achieving TV means 100% score. We assume that achieving values beyond the TV does not improve the CSR. The QFD TVs are determined together with the voice of the customer and they reflect some balance among customer's needs, capabilities, tradeoffs and benchmarking with the market leaders.
2. The poorest end of the range has a low CSR value (not necessarily zero). PCs values below the worst end score the same low CSR value.
3. The CSR values between the TV and the poorest end are distributed according to the CSR function as agreed upon during the QFD together with the customer.

We shall illustrate the DQM with the example of flashlight for the elderly. The conceptual design of the flashlight is found in [2]. Customer satisfaction from the flashlight weight varies according to the total weight of the flashlight example.

\[ \text{CSR} = \begin{cases} 
1 & \text{if Total Weight} \leq 40 \\
0.9 & \text{if} 40 < \text{Total Weight} \leq 60 \\
0.8 & \text{if} 60 < \text{Total Weight} \leq 80 \\
0.7 & \text{if} 80 < \text{Total Weight} \leq 100 \\
0.5 & \text{if} 100 < \text{Total Weight} \leq 120 \\
0.3 & \text{if} 120 < \text{Total Weight} \leq 140 \\
0.1 & \text{if} 140 < \text{Total Weight} \leq 160 \\
0 & \text{otherwise}
\end{cases} \]

Figure 1: Customer Satisfaction Rating (CSR) function for the total weight of the flashlight example
The TV is 60 grams. For this value the CSR is 100%. Smaller weight will not improve the CSR but will not lower it either. 240 grams or more will reduce the CSR to 40%. Within the range of 60 - 240 grams the CSR decreases as the weight increases.

The methodology uses some types of CSR functions: Continuous (linear or non-linear) functions. Figure 2, for example, shows a typical cost CSR function, step type function, or multi-dimensional function, used when the CSR depends on more than one variable or when the value of one PC depends on another one.

4.5 Integration of the deployed metrics.

Metrics that were deployed to parts, assemblies, processes and production - controls (vertical deployments) or those who were deployed to metrics of costs, time to market, reliability, safety, maintainability or weight (horizontal deployment) are integrated in the same “sum-product” way.

4.6 DQM conclusions

DQM has been considered as a challenging issue for decades. This paragraph describes a new method for DQM, based on the results of QFD. The method defined for each PC a CSR function which defines the degree of customer satisfaction according to the value achieved for that PC. The QFD team determines the customer satisfaction distribution together with the voice of the customer. The paragraph presented and illustrated the process of metrics selection and evaluation, types of PC's metrics and types of CSR functions.

The basic deployments of customers' needs (system PCs, vertical deployments and horizontal deployments), when combined together, provide us with an integrated framework for DQM. In this way the basic attention is given during the new product development process to each one of the critical aspects to the customer and to the developing organization. However, a practical application of deployments in DQM requires comprehensive implementation of QFD across the organization as a way of living for all the product development teams.

The DQM system presented in this paragraph is an integral part of the ICDM methodology for conceptual design of new products. More details on DQM, and more examples can be found in [17]. The authors believe that the benefits of a company-wide application of design methodologies like QFD or ICDM can increase significantly when the methodologies are combined with an on-line DQM and control system as proposed.

5. Conclusions

The stages of conceptual design were developed in Germany and summarized by Pahl & Beitz. The comprehensive work of Pahl & Beitz is considered to be the cornerstone for any work on conceptual design and their book is the basic textbook for engineering design classes and practice. The method has been extended by introduction of new techniques and tools, that enable to be more specific and more focused and fit to the Israeli way of thinking. The extended design methodology is called ICDM – Integrated, Customer Driven, Conceptual Design Method and it fits to the whole conceptual design process from the definition of a need until the selection of the optimal concept.

Three out of the seven new ICDM tools were shortly described in this paper. These tools are the Enriched QFD for task definition, the CFMA – Conceptual Failure Mode Analysis and the DQM – Design Quality Measurement to evaluate the satisfaction from the generated concepts. ICDM has been used extensively in many Israeli start-up companies and also in classical industrial companies that adapted the method to their special needs.

As all aspects of conceptual design are extremely important, it is not easy to emphasize only a few. But based on our experience, the strongest additional tools, that substantially contribute to the designers work at generating new concepts are the CFMA that helps to reject marginal concepts and improve the good ones, and the EQFD that provides a quantitative tool how to include exact requirements in the specification and reject those that are superfluous. Therefore late, sometimes major changes, and initially unneeded work are saved.

ICDM has quite a few steps in addition to the Pahl & Beitz method and its full use contributes substantially to good design, but designers are very busy people and they quite often use only parts of the method, like one or more of the tools that fit to their immediate needs. It happens to the P&B original method too. That shows not a weakness but rather a benefit of the methods, as often with small effort high achievement can be reached.

ICDM is a well proven and successful Israeli method for conceptual design, based on the Pahl & Beitz methodology. It is well known in Israel, as it is a main course in five or more curriculums for MSc in System Engineering and also in undergraduate ME courses in the Technion. It has not spread outside Israel, except in Australia, probably because a basic book has not been written. Probably such book should now be prepared. Alternatively, or additionally, a supplement to the Pahl & Beitz method may be considered to be included in the future manuscript updating.

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References

[1] Pahl G. & Beitz W. Engineering Design a Systematic Approach, Springer, 1977-2014, 8 editions.
[2] Hari & Weiss, 1996, ICDM: An Inclusive Method for Customer Driven Conceptual Design, Proceedings of the second annual Total Product Development symposium, Pomona, CA, Nov. 1996.
[3] A. Hari, J. E. Kasser and M. P. Weiss, "How lessons learnt from creating requirements for complex systems led to the evolution of a modified version of QFD and a proven new meta-methodology", Systems Engineering, vol. 10, No. 1, 2007 pp. 45-63
[4] A. Hari, J. E.; M. P. Weiss, Lessons Learnt From the Applications of QFD to the Definition of Complex Systems Proceeding of the Annual International Symposium of the International Council On Systems Engineering (INCOSE), Orlando FL, USA, July 2006 (Best paper Award)
[5] Hari, A. and Zonnenshain, A., "Quality Function Deployment (QFD) In Complex Systems", the National Conference of the Israel Society of Quality, 1993.
[6] Cohen, L., Quality Function Deployment: How to Make QFD Work for You, Pearson Professional Education, 1995.
[7] King, B., Better Designs in Half the Time, Goal /QPC, Methuen MA, 1989
[8] M.P. Weiss and Y. Gilboa, More on Synthesis of Concepts as an optimal combination of solution principles, Design 2004, Dubrownik
[9] A. Hari and M.P. Weiss, CFMA – an effective FMEA tool for analysis and selection of concept for a new product, DETC/DTM-8756, ASME, Las Vegas 1999
[10] Stamatis H.D. (1995), Failure Mode and Effect Analysis: FMEA from Theory to Execution, ASQC, Quality Press’ Milwaukee, Wisconsin
[11] Mayersdorf, 1994, R&D Quality and Productivity: Measurement and Improvement Process, D.Sc Thesis, Technion -ITT
[12] Below & Bass, 1992, Metrics Implementation: Establishing a Metrics Program, EDS Technical Journal, Vol.6,NO1,1992.
[13] Nichols, 1992, Better, Cheaper, Faster Products by Design, Journal of Engineering Design, Vol.3,N2,1992.
[14] Meyer & Stevens, 1993, Measures for Integrated Product Development, Concurrent Engineering, EDS Publications.
[15] Gale, 1994, Managing Customer Value, The Free Press, New York, N.Y.
[16] Hauser & Clausing, 1988, The House of Quality, Harvard Business Review, May - June, 1988
[17] Hari, Weiss, and Zonnenshain, 2001, Design Quality Metrics Used as a Quantitative Tool for the Conceptual Design of a New product, Proceeding of ICED 01, The 13th International Conference on Engineering Design, Glasgow, UK, 2001. (Best Paper Award)
[18] Hari A., Shoval S. and Kasser J.: Conceptual Design to Cost: A new systems engineering tool, Proceeding of the Annual International Symposium of the International Council On Systems Engineering (INCOSE), INCOSE 2008, June 2008, Utrecht, the Netherlands.
[19] Kraus J., Weiss M.P. and Hari A.: Design to Withstand Improper Use and Design for Future Enhancements, are Incorporated in the New Robustool Proceeding of the International Conference on Engineering Design, ICED’07, 28 - 31 August 2007, Cite Des Sciences B.De L’Industrie, Paris, France.
[20] Hari A. and Weiss M.P.: Analysis of Risk and Time to Market During the Conceptual Design of New Systems, Proceeding of the international conference on engineering design, ICED 03 Stockholm August 19-21, 2003.