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MORE ON SYNTHESIS OF CONCEPTS AS AN OPTIMAL COMBINATION OF SOLUTION PRINCIPLES

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1. Introduction

Conceptual design is considered as the most important step in the design of a new product. There the performance of the product is generated and about 75 % of the life cycle cost (LCC) is committed. An important step in conceptual design is the synthesis of solution principles into many concepts, so that the best one can be selected as the concept for the new product. Synthesis by morphology has been introduced many years ago (Zwicky 1976) and is considered a valuable and practical tool in the design of new concepts. The use of morphologic maps made synthesis straightforward, so that many different apparent concept variants could be easily generated, actually many hundreds of them or even thousands, based on the number of sub-functions of the new product and the number of solution principles for each sub-function. However, the large number of possible combinations is also considered as the deficiency of the method, since the number of variants that a designer is capable of generating and evaluating is obviously limited, and the best combinations may be overlooked. Therefore morphology has been criticized as an inefficient method to synthesize a new optimal concept. One feasible method to extract the best combinations out of the many existing possibilities, by the name "Indirect Synthesis Method", has been introduced by the authors [Gilboa et al, 2001]. The current study is considered as another simple and effective technique to find the best possible set of combinations of solution principles by the name of "**Direct Synthesis Optimization**" – or **DSO**, a straightforward method that works. The "Direct Synthesis Optimization" method is an inherent part of **ICDM** as described here. The study includes also the "**Enhanced Direct Synthesis Optimization**", that contemplates the same problem, and will be fully reported separately. The proposed method has been tested only for the conceptual solution synthesis.

2. The ICDM method

ICDM is an **I**ntegrated, **C**ustomer **D**riven **C**onceptual **D**esign Method that has been optimized for the design of a new and original product. Its first version was originally introduced in 1996 [Hari & Weiss, 1996], and it was enhanced since. The method covers the entire conceptual design process, from the definition of the new need up to the selection of the optimal concept. It has an open architecture, is flexible and tailored to the unique needs of each case or organization. **ICDM** is a prescriptive conceptual design procedure that is conceived for a Product Development Team – PDT, in a modern high-tech company. It is based on an interdisciplinary engineering team, but does not oblige the availability of a professional inventor or unique personality. **ICDM** is based on a few existing, well known techniques, combined with several additions, extensions and full integration. **ICDM** has been introduced to and often used by the sector of the modern high-tech industry in Israel. Most of the applications are considered as commercial secrets, but a few successful applications have been reported in technical conferences [Issers & Volansky 2000, Leibovitch & Volansky 1999]. The procedure of **ICDM** consists of 10 steps, where a few of them have been well established and others, designated by **bold** letters, are **original**, as follows:

Table 1. The 10 steps of ICDM

No.	Step	No.	Step
1	Identification of the customers and of their needs.	6	**Sorting the solution principles and Synthesis to create a small cluster of potentially best and feasible concepts** (The current study)
2	Translation of the **V**oice **O**f the **C**ustomer (VOC), into the product definition and specification, using an **original enhanced QFD**.	7	The initial evaluation and selection of a few main concepts for further design steps.
3	Abstraction and definition of the basic problems – the sub-functions.	8	Design, architecture and analysis of the main concepts **by original techniques – CFMA, CDTC and RTA**
4	Creation of many engineering solution principles for each sub-function, shown graphically on a morphological diagram,	9	Selection of the winning concept – **a full second round of selection**
5	**Definition of criteria for the concepts evaluation and selection**.	10	Project Launch – initiation of the embodiment design, based on the winning concept.

Step 8 of ICDM includes the architecture of the main concepts. The task of the PDT is to develop the concepts further, so that the final selection can be made. In this step, the first draft design is generated and the basic form and architecture of the new product is outlined. This task also includes conceptual decisions on the production process, main materials, technologies, assembly, operations, maintenance, testability policy, handling, storage and transportation and other support policies. An additional task of the team, at this stage of design, is to perform several analyses on the product level, based on the evaluation criteria set in Step 5. **ICDM** includes a set of universal evaluation tools, designed specially for the constraints of the conceptual design phase, when time is limited and information is scarce. These tools consist part of the general risk analysis that has recently became very popular and required for any design. Two of these special tools are aimed at cost and time-to-market evaluation. A conceptual, product cost evaluation method is based on the Pareto Cost Evaluation. The method is based on the principles of the Design to Cost (DTC) technique, on the Pareto principle and on organizational experience, rather than on detailed product and process design. It helps the PDT to evaluate the major manufacturing costs of the alternative concepts, when information is still very limited at this early stage of the design process. The risk and time-to-market analysis - RTA is based on the “knowledge gap” principle [Hari et al. 2002] and on organizational experience. It considers the product development cycle as a process of closing the knowledge gaps, the gaps between the current state-of-the-art in the company and the additional knowledge in technology that is needed and has to be developed or acquired for the new product development. The third technique used is CFMA – the Conceptual Failure Mode Analysis Method [Hari & Weiss 1999]. A conceptual failure mode analysis is based on functions and specific organizational experience, rather than on detailed designs, which are not available at this stage.

3. The synthesis of solution principles

Following the construction of the morphological diagram in step 4 of the **ICDM**, one has to combine various solution principles of the sub-functions into conceptual solutions for the main function, namely for the final product. This is the synthesis step and many possible combinations have to be generated. One solution principle of each sub-function has to be chosen and combined as part of each final product combination. Some of the combinations produce very good solutions, some are poor and some might be very impractical because of incompatibility between the different solution principles. The procedure is shown symbolically in figure 1.

The current practice is as follows: Each person of the PDT - Product Development Team selects intuitively one or more combinations. All these selected combinations are defined as the initial group of concepts. The combinations are drawn on the morphological diagram by lines, as shown in figure 1. The lines are combinations of solution principles that form potential solutions to the main function.

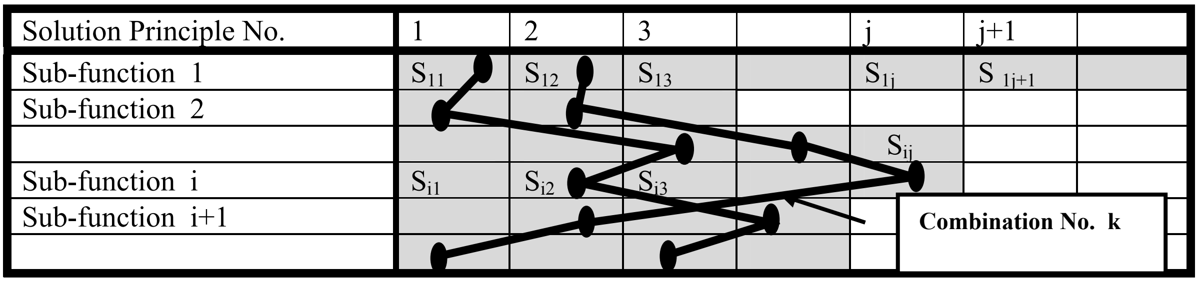

Figure 1. A symbolic morphological diagram of solution principles for the sub-functions, so that S_{ij} is the j-th solution principle of the i-th sub-function

The PDT chooses from this group a reduced number of combinations that are the cluster from which the winning concept will later be chosen. Pahl & Beitz (1996) reviewed this step and proposed techniques how to synthesize the better combinations. The techniques were mostly intuitive, by using elimination of the less contributive principles and by locating incompatibilities between the solution principles. The current study included comparison between intuitive and the new proposed methods. There are two main problems in this procedure:

1) The experts may overlook the best combinations in their synthesis. Usually the number of possible combinations is extremely large (e.g., 26460 combinations in one presented case, [Leibovitz & Volansky, 1999], and it is almost impossible to find manually all the potentially good combinations).
2) Team members tend to prefer their own selected combinations rather than judge objectively the other combinations in the initial group of concepts. A dominant team member may force his solution to be the winning concept chosen by the PDT [Issers & Volansky, 2000].

Another problem that has to be taken into account is the constant and chronic lack of time under which the PDT is working. In spite of the known fact that the conceptual design is the most important and most influential on the prospects of the new product, the reality is that the PDT works under tremendous pressure, because its members are busy with the running projects and their current problems and cannot devote the needed time to new projects. Therefore only extremely simple and effective methods will be accepted by the PDT, methods that will show immediate results and will not be time consuming, in learning the methods and in using them. The PDT has always the classical option of using intuition, which "after all is not such a bad alternative and it worked well in the past".

To partially overcome the difficulties, two different algorithms for choosing the initial group have been introduced, namely the direct and the indirect methods. Both methods overcome these two problems. In both methods, the experts do not directly select the combinations which will be included in the initial group, and thus their final judgment of the initial group of concepts tends to be less biased. It is the aim of the synthesis algorithms to pick up a group of 10 to 15 combinations that have the potential to be the best in the group. The subsequent steps are performed manually by the PDT and the final selection of the winning concept is a fully-manual team assignment.

In spite of the use of the term "**Optimization**" in the following chapters, in Engineering Design any optimization is to be understood as a "**Local Optimization**" that considers only the known solutions, and those generated by the designers, and never a "**Global Optimization**". In Design, a new solution, that is better than those that have been considered and selected, may always emerge and be introduced. To be selected, the advantage of one design solution compared to others, has to be a **real, substantial advantage** and not a thin statistical margin, because an experienced designer will always make the final decision based on **his intuition**, and never on narrow computed differences.

4. The Indirect Method

A sample of full combinations of solution principles is selected by an algorithm and is evaluated by the team members. Based on these data, using statistical techniques of factorial experiments, scores can be estimated for all combinations of the morphological map. The initial group of concepts is obtained as output of the algorithm, which chooses the combinations with the highest estimated scores. The proposed method is similar in its basic idea to the technique known as “Conjoint Analysis” used in marketing [SAS, 1993]. Conjoint Analysis borrowed the terms and methods from the area known in statistics as “Design of Experiments”, which is often adopted to solve engineering problems. The indirect method has been reported by the authors in the past, [Gilboa et al, 2001], and will not be shown here.

5. The Direct Synthesis Optimization - DSO

The direct method is based on evaluation of each solution principle on two scales, one is its contribution to the performance of the new product, and the second is the potential risk that integration of such solution principle may expose the product to. These two evaluations will be expressed in two distinct marks for each solution principle. The mark has to be graded by the development team in consensus, therefore it has to be graded on a very simple scale, so that the decision will be easy and not time consuming. Later, the compatibility of the solution principles, one to each other has also to be accounted for. The evaluation methods will be detailed here.

5.1 The ranking scale

The simplest scale to enable very fast and simple decision should be a scale of three, namely: good, average and poor. However, such a grading system will obviously bend the results too much to the center, therefore the center evaluation will be divided into two – namely "better than average" and "less than average". So that the ranking scale will actually be a scale of four grades, but it will be extended to emphasize the differences, as shown in table 2. This scale was found to be easy to use and evaluate even by teams, and will be used all through this study, for the performance of the solution principle and for the potential risk involved. The low score for bad solution principles was chosen zero so that bad ones will be eliminated, as too many are available, and it will be easier to use in computerized algorithms.

Table 2. Ranking scale for solution principles

Mark	Description
5	Good to excellent
3	Better than average
2	Less than average
0	Poor

5.2 Performance and risk ranking

Each solution principle is designated in the morphologic diagram, in figure 1, as S_{ij}. In a real and not symbolic diagram, such as in figure 3, it is also depicted with an icon. The evaluation of the solution principle, as mentioned before, has to be done on two separate issues. The first is its contribution to the **performance** of the product and the second is the amount of **risk** that its realization may expose the product to. These evaluations are made by the team and should be decided by consensus, therefore the method has to be simple, with not too many possibilities and straightforward.

The contribution to **performance** is not difficult to estimate, as the performance parameters have been detailed generally in the specification that has been prepared at step 2 of **ICDM**. The question to ask is whether including the certain solution principle in the product will enable to fulfill all the needed parameters. If the answer is "yes", then it is a good or excellent solution principle and its evaluation is **5**, if the answer is "most" and including the important ones, then the evaluation will be **3**. If the answer is "no", the solution principle enables to fulfill only a few of the requirements, or not the important ones, the grade will be **2** or **0**, as per the team's evaluation.
As to the **risk** in each solution principle, three different considerations have to be considered, as follows:

a) Are there any uncertainties or **knowledge gaps** in the design stages (like the need to develop a new technology or so) that may extend the development time and cost beyond the plan? (Not info-gaps that can be closed without technology development)
b) Are there any problems in production that may need extended investments, or costs? For example – can we use our current production machines or we have to invest in new, or are we familiar and experienced with the production technology, or a new one has to be acquired or developed?
c) Are there any problems in use or in maintenance of the products that may provoke customer un-satisfaction? Is any of them too complicated, too expensive or too time consuming?

Based on these considerations the risk grading is straightforward. If the solution principle does not excite any of the above problems, then there is no anticipated risk and the mark is **5**, if one problem of the above exists, then the mark will be **3**, when two exist – the mark will be **2** and when all exist then the mark will be **0**. The list is a simplistic first approximation only, and it can be changed according to the wish of the team, based on the level of the specific problem or knowledge gap, etc.
For example, the knowledge gap in the needed technology is identified as substantial, which may prolong the development time to much longer than available, and/or extend the costs to control the new technology to much higher investment than expected, or even prohibitive levels and therefore the risk will be assigned as high, and its mark will be 2 or 0, even if there are no expected problems in manufacturing and in maintenance.
The two marks will be written in the diagram for each solution principle as shown in fig. 2.

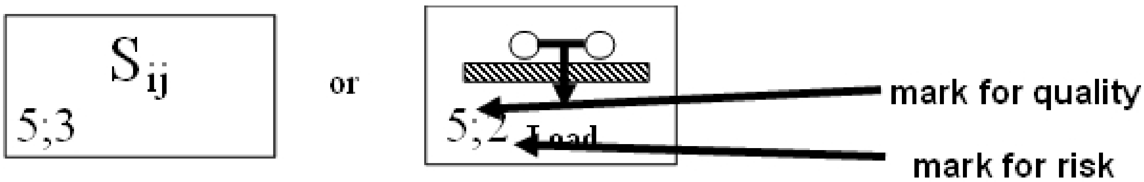

Figure 2. Designation of the quality of a solution principle, as shown in the two boxes in the morphologic diagram

In the left box, the grade for quality is **5** and for risk is **3**, in the box on the right side the evaluation of quality grade is **3** and the grade for risk is **2**.

5.3 Solution principle ranking

Now all the solution principles in the morphologic map have been graded, and the score is written in the left side of each box. The pairs of evaluations have now to be ranked, as to the overall quality, so that the solution principles will be ranked in the diagram in a descending order.

Table 3. Ranking of solution principles evaluation, for two types of products

Product	Mark	Product	Mark
In which the **performance** is the main parameter	5;5	In which **economy** and the **TTM** are the main parameters	5;5
	5;3		5;3
	5;2		3;5
	3;5		3;3
	3;3		5;2

The proposed ranking is the following: **(5;5)** is the best, **(5;3)** follows. The subsequent pairs are somewhat problematic. If the performance of the new product is crucial and the main issue, then the next pair will be **(5;2)** that promises high performance, even at the risk of higher price or longer development time, and then **(3;5)** and **(3;3)** that have lower performance but less risk is associated. If on the other hand the price is the main issue, then **(3; 5)** and **(3; 3)** will precede **(5; 2).** All other pairs should be abandoned, as low quality solutions. The ranking is flexible and can be adapted to the relevant case, the scale is shown in table 3. The ranking scale is flexible and every team can decide about a different ranking, based on the project type. In certain cases, the ranking scale for each sub-function can be different, because the contribution of one or more sub-functions to the performance of the whole product may be dominant as compared to the other sub-functions and an appropriate scale can be selected for each

5.4 The Synthesis Method

Based on the evaluation for quality and risk, and the ranking of the pairs, a modified morphologic diagram, that will greatly enhance the possibilities of locating the optimal solutions, can be prepared. The location of the solution principles for each sub-function on the diagram will now be **rearranged** according to the order of ranking described in 5.3. A typical such modified diagram is depicted in figure 3. In the figure the lines that combine the selected solution principles into full sets of prospective concept variants are depicted. It is obvious that now the lines that combine only the principles with the higher scores, namely the ones on the left part of the diagram, are potentially the best combinations. It is extremely rare that a combination that includes a low graded solution principle will be a candidate to be chosen as a good concept variant.

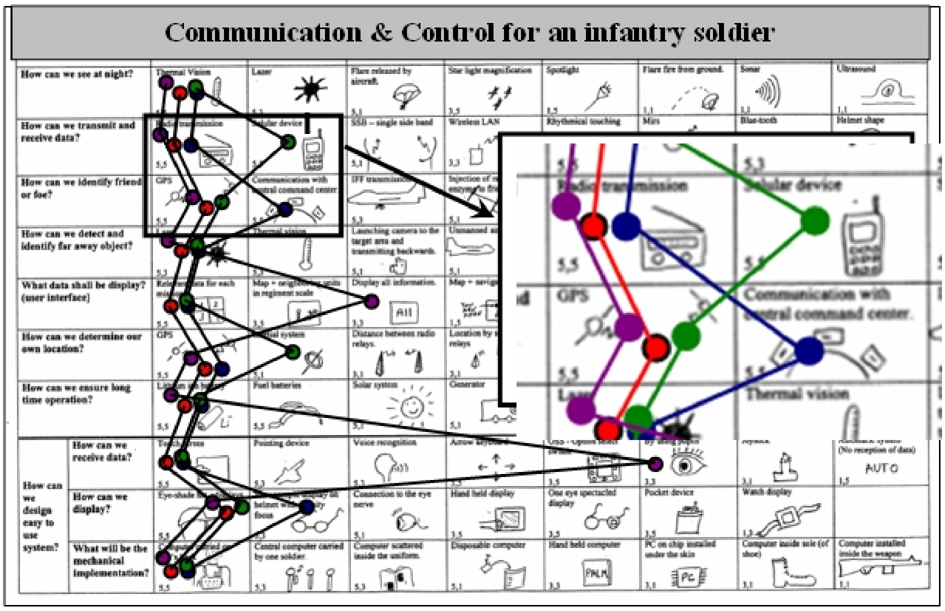

Figure 3. The Morphologic Table, with combinations of Solution Principles depicted on it. A few of the better combinations are shown on the left part of the diagram

Therefore, even without any further algorithmic activity, a well-chosen number of combinations of potentially best concepts can be easily synthesized. The first one will be the vertical line on the left, that combines the solution principles that have the best potential in each line. The second will include one or two changes that switch to the adjacent solution principles that have the highest mark, and so on, as can be seen in figure 3. The reason that the first vertical line of combinations is not always the best concept variant, is the possible incompatibility of certain solution principles, one to another. The incompatibility can be technical, like certain materials that cannot be combined, or shapes that contradict etc., or economical, for example two sub systems that are run by different kinds of motors – one electric DC and the other hydraulic and their utilization will require two different power supplies. Good compatibility of solution principles is an important issue for all concept variants. Compatibility must be kept between all solution principles in each combination. A preliminary test for compatibility, is included in the enhanced synthesis method of theoretical combinations is extremely large and it is not practical or possible to perform such evaluation on all of them. Compatibility is checked, in the proposed method, for the group of the selected combinations only, and any incompatibility causes the combination to be rejected and other one to be synthesized.

In practical cases, a few solution principles that seem not to be the best available are selected within the choice combinations. The reasons for such selection can vary, but here are some practical possibilities:

- A very novel solution principle with great impact on the performance of the designed product has been selected, in spite of the fact that the risks in such selection are considerable. Such a solution principle may have a mark of (5;2) or even (5;0). Now in the selection of the subsequent solution principles for the other sub-functions, the more conservative solutions may be chosen, so that the additional risk will be reduced, and their marks may be (5;5), (3;5), or even (2;5).
- A new product is being developed in a case where the TTM - time to market is very crucial. Here the risks must be minimized on behalf of performance, and therefore no solution principles with the mark less than (*;5) will be chosen.

The rearranged morphological chart in itself is a very usefull tool for the experienced designer. His possibilities of selecting the best combinations are easy to locate and the risks, or price are clear. So that the method up to this point is of considerable value. About 15 valid combinations are synthesized, for further design activities.

The method up to this point will be called the **"Direct Synthesis Optimization"** method, or the **DSO**, and as will be shown, its user will achieve a very significant improvement over regular intuitive combinations. The **DSO** method is a simple combination method that works, without excessive time investment, and will most probably be preferred by experienced and novice designers. To contemplate the compatibility problem, a more advanced method, called the "Enhanced Direct Synthesis Method" will be described later in this study.

6. The Enhanced Direct Synthesis Optimization

It is clear that the easiest way to achieve good combinations is when the basic problems are independent of each other and no compatibility issue arises. In the many projects when this may not be the case, the information about the incompatibilities adds useful information to the synthesis stage. Incompatibility can be between two solutions principles in the group, or three, or more. There is a possibility to check these incompatibilities and eliminate the combinations that include them. To do so, one would have to look into all possible combinations, which are a huge number and the effort would be prohibitive. In this study, only the compatibilities between any two solution principles, belonging to different functions (or lines) have been considered. All incompatible pairs have been eliminated in the combinations, and a special computerized algorithm has been used. The fact that the higher level compatibilities have been neglected caused the developed algorithms to include a small number of non-optimized combinations that have to be eliminated manually. This is hardly a deficiency, as all designers want to make the final decisions themselves and have the "final touch", and no experienced designer would trust purely algorithmic solution generation and selection. The method that contemplated the a-priori analysis of combinations is called the Enhanced Direct Synthesis Optimization method - the EDSO. The EDSO will be described in a separate paper.

7. Experimental results

6 teams in our experiments were students in an advanced engineering design course that is part of a graduate program in Systems Engineering in the TECHNION, brought together by three engineering faculties: Mechanical, Industrial & Management and Aeronautical. All of the participants were experienced engineers, working in modern high-tech industry for at least three years and in some cases for many years, some in technical middle management positions. The class was organized into teams of five to six students, each of them had to develop the concept of a new product using the **ICDM** tools. At first they did all the ICDM procedure without using the Design Synthesis Optimization. Then they were presented the algorithmic initial group and compared it with their intuitive results. Three out of the 6 teams used both algorithms, 2 preferred the indirect method and 1 preferred the direct method. For all teams the algorithmic initial group of concepts was better than or at least as good as the intuitive one. In all valid cases the algorithms presented **1 or 2 combinations**, which were evaluated as **much better** than the intuitive winning concept. Many of the combinations in the algorithmic initial group of concepts were identical to those chosen intuitively, or evaluated as good ones by the teams. In every algorithmic initial group of concepts, 2 to 6 combinations were evaluated by the teams as poor, and had to be eliminated, because of the incompatibility problems, or other issues. Eight other teams used the DSO method, and the results were compared to 33 teams that did not. A hypothesis that there was no difference between the two sets was rejected by the Mann Whitney Wilcoxon Method with significance level of 5%. A full set of statistical results, that are part of a PhD Thesis will be reported separately.

8. Conclusions

- The DSO is a simple method that works. Its use demands the same amount of effort for preparing the data for the algorithms, as the work that was done in the intuitive synthesis.
- The use of the Direct Synhesis Optimization method caused to generate at least one new better concept than those that were chosen by the Design Team intuitively.
- The re-arrangement of the Morphologic Diagram by ranking is by itself an efficient synthesis step.
- Many of the intuitive combinations, and the winning concepts of the teams, were also chosen algorithmically, both by the DSO and EDSO methods.
- The DSO, EDSO and the Indirect methods should be seen as efficient helpful tools for the Design Team members. However, the final contribution and selection of the winning concept and the elimination of the unfitting combinations is a fully manual assignment.

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