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DESIGN TO WITHSTAND IMPROPER USE AND DESIGN FOR FUTURE ENHANCEMENTS, ARE INCORPORATED IN THE NEW ROBUSTOOL

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ABSTRACT

ICDM is the **I**ntegrated, **C**ustomer **D**riven, **C**onceptual **D**esign **M**ethod, that has been developed for the design of new optimal products. The Robustool has been developed and added as part of step 8 of **ICDM** – the preliminary design. This new tool is aimed, among other tasks, to ascertain that the new product will withstand illegitimate operation, namely activation in circumstances that are out of the formal specification, but that may happen in real life. An additional benefit that was included in the Robustool is the formal prediction of future enhancements and new models of the product and inclusion of attributes that will enable easy and inexpensive upgrade to the new models.
The Robustool has been built as a quantitative checklist that enables to compare new concept variants, and the ability to design them to fulfill these robust requirements. It is adapted to the phase when many details of the new concepts design are not available yet.

As conclusions of the initial use of the Robustool we can emphasize that: the Robustool is an easy to use and powerful tool that helps the designer and the system engineer to enhance the robustness of the product or the system when at the concept stage. Moreover, it gives the engineer a score of the future anticipated robustness for each concept variant, that can be used in the selection of the winning concept. The Robustool can be easily adapted to any kind of systems in order to get the highest benefit of this tool. The use of the Robustool at the concept stage, enables any organization to achieve a robust design, robust production and robust use of the system when it comes to market. The application and the benefits of the Robustool are demonstrated through a case-study.

Keywords: Robust Design, Robustool, future enhancements, improper use

1 INTRODUCTION

Penetrating the global market of the "global village" with new product or system requires many preparations, careful definition of the specifications and the generation of a winning concept for this product. While doing this job the constraints that are forced and blocked by the market must be taken into account. It means that many degrees of freedom are blocked – the price by the market forces, the performance by the existing product etc. An important degree of freedom that is crucial for a successful product, is at the hand of the designer – it is the comprehensive robustness of the new product.
Robustness is the ability of the system to avoid failure modes in the presence of noise [1]. Noise is any kind of activity that is outside the bounds of the specification**.** The robustness gives the user the benefit that the product will always survive, even in cases of misuse or exposure to out of spec conditions. The robustness gives the organization the ability of smooth production, low rate of maintenance and low cost of upgrading to a new model.

Robust design was developed by Taguchi. His main activity was making performance of products robust in the presence of noise. By noise he meant variations due to environment, production and time. Very detailed methods, how to overcome this noise are described in the reference [1]. Clausing and Fey at reference [3]. included the analysis of failure modes and effects in all steps of the product design and development, as part of robust design and used the expression "operating window" as another parameter to consider. The operating window is the clearance between the lower limit of parameters that ascertain the successful performance of a product and its upper limit, and the broader this clearance is, the more robust is the product.

The existing tools for robustness are necessary and extremely useful, but only at the embodiment stage. In the earlier, methodical conceptual design of a new product many concept variants are generated. In the process of selection of the winning concept the potential for the ability to later design this concept as a robust one, must be considered as an important attribute in the selection. The existence of a proper tool that can predict the robustness ability at the concept stage has not been reported, and is needed.   The aim of this study was to develop a new design tool that will provide an additional evaluation parameter – 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.

2 ROBUSTNESS OF A CONCEPT AND HOW IT CAN BE TESTED

2.1 Robustness of concept – What does it means?

Robustness is defined, as mentioned above, as the ability to prevent failure modes in presence of "Noise". Noise is any kind of operation outside the defined specifications.
A system is considered as robust if it would operate close to its specs and certainly will survive even in case of misuse or if activated outside of its specifications.
It is proposed that Robustness may have a wider meaning –

- Future enhancements, new models of the product and inclusion of new attributes will be implemented easily and inexpensively.
- The production will flow smoothly even in cases of small defects at the components or replacement of some components with similar ones instead of identical.
- The sub systems of the product are independent of each other so that malfunction of one will not cause total failure.

Every system or product has four stages till it reaches the market: concept, full scale development, production and use. In order to get a robust product at the using stage there must be an "And" function of the robustness at all previous stages. This means that the robustness at the concept stage has to take into account the robustness of the design stage, the robustness of the production stage and the robustness of the usage stage as well, as described at Fig 1. The conclusion is that the robustness plays a major role even solely for the fact that it is considered at a very early stage.

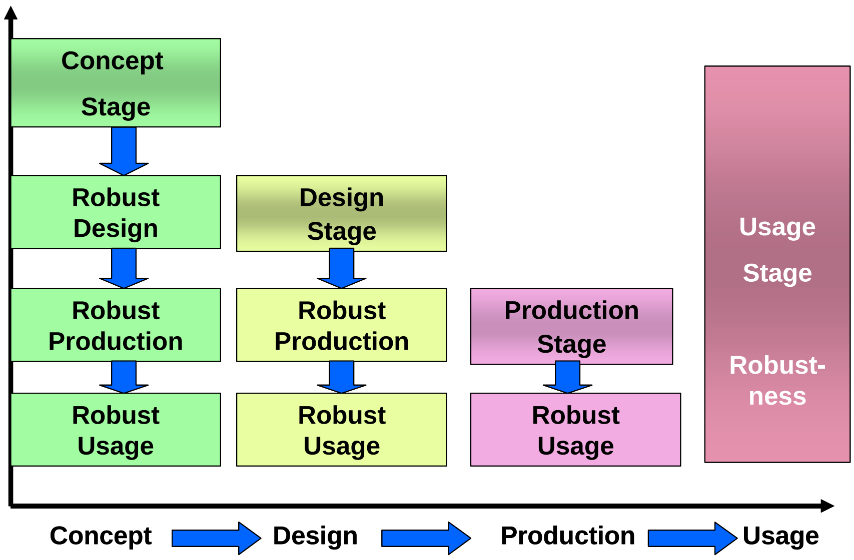

Figure 1. Robustness from Concept to Usage Stage

2.2 Robustness Test as a part of the ICDM

ICDM is the **I**ntegrated, **C**ustomer **D**riven, **C**onceptual **D**esign **M**ethod [4] has been developed for the design of new optimal products and has constantly been enhanced since [9]. Recently the Robustool has been developed and added as part of step 8 of ICDM – the preliminary design. This new tool is aimed, among other tasks, to ascertain that the new product will withstand unlawful operation, namely activation in circumstances that are out of the formal specification, but that may happen in real life. An additional benefit that was included in the Robustool is the formal prediction of future enhancements and new models of the product and inclusion of attributes that will enable easy and inexpensive upgrade to the new models.

The 10 steps of the ICDM are demonstrated in table 1. It, is based on the original Pahl & Beitz studies [8], and integrates some well known methods with a number of original design tools and techniques. The integration and the tools designated in red and italics in table 1, are original developments, a few of them have been reported in the past in ICED conferences [9-14]. Quality requirements in a new product definition have been dealt with [9] and step 2 of ICDM can benefit by them.

Table 1. The 10 steps of ICDM

No.	Step	No.	Step
1	Identification of customers and their needs.	**6**	Concept Synthesis by the ***DSO*** and ***IDSO***
2	Translation of the **V**oice **O**f the **C**ustomer (VOC), into the product definition **QFD**.	**7**	Evaluation and selection of a few main concepts for further design (Pugh)
3	Abstraction and definition of the basic problems – the sub-functions	**8**	Design, architecture and analysis by use of ***CFMA, CDTC, RTA*** and the ***Robustool***
4	Creation of many solution principles demonstrated on a morphological diagram,	**9**	Selection of the winning concept by a ***second round*** of concept selection
5	*Definition of criteria for the concepts evaluation and selection*	**10**	SDR and Project Launch initiation of the embodiment design

DSO and IDSO are Direct and Indirect Synthesis Optimizations, CFMA – is Conceptual Failure Mode Analysis, CDTC – is Conceptual Design To Cost, RTA – is Risk and Time to market Analysis.

ICDM has been proved to be a very efficient tool for design and is currently in use by many Israeli High-Tech companies. The Robustool is part of the preliminary design, in step 8 of ICDM, and plays an important role in the concept selection in step 9.

2.3 The Robustool

The need for a quantitative tool that will aid and guide the system engineer and the designer to achieve a robust concept by getting an objective score of the robustness is obvious.

Taguchi [1] uses the signal to noise ratio as a measure of robustness. Some publications describe and explain what is robustness without any tool how to measure this property, others deal with the robustness at the production stage and not at the concept stage and yet others suggest a so complicated tool that it is almost useless to a busy systems engineer [2],[3], [7]. The aim of the Robustool is to provide the engineer and the system engineer with a simple, powerful tool to measure and to improve the robustness of the product or the system even at the conceptual design stage when almost of the details on the new concepts design are not available yet.

The research methodology of of this study , like in other tool development techniques, is based on testing the proposed new technique on several practical case studies and evaluation of the results. Such evaluation will be qualitative rather than statistical or quantitative, because previous examples did not include quantitative parameters, like the robustness or future model attributes. But the results of using the Robustool are very clear and straightforward, therefore a few case studies will suffice to justify the use of the new tool.

The structure of the Robustool is as follows:

2.3.1 The Parameters / the Questions

- The Robustool is an EXCEL based file with a check list that has to be answered by the user. The allowed answers can be: Yes, No, N/A (Not Applicable). All other answers are blocked.
- The answer "Yes" always means that the concept is robust and the answer "No" always means the contrary.
- The rationale of every question is attached to the question, so there is no waste of time by looking for the rationale or what the question means.
- The questions are branded to four categories:
  - Definition of the environment conditions that the product supposed to be exposed to and the parameters that are expected to be changed when an upgrade to a new model will take place.
  - Questions that deal with the robustness at the full scale development stage.
  - Questions that deal with the robustness at the production stage.
  - Questions that deal with the robustness at the usage stage.
- The question are also categorised to two severity categories:
  - "A" – for questions that are critical for system robustness. These answers are highly weighed at the score calculation.
  - "B" - for questions that are important for system robustness. These answers are weighed with lower weight at the score calculation.
- Every user can add his own questions, relevant to the case, according to his experience and needs.

2.3.2 Robustness measurement

After filling the tables with "Yes" and "No", the Robustool gives the user a score that is useable twofold:
1. As a quantitative parameter of robustness that plays an important role in the concept selection step (No. 9 of the ICDM).
2. As a quantitative parameter to know if the concept is robust enough, if some improvement is needed or if major improvements are needed and the design must go back to square one. The connection between the score and the robustness evaluation is shown in Table 7:

The function that calculates the score is not a linear one in order to be lenient when there are only few "No" answers and to be stringent when the number of these answers increases.
The score calculating function is:

$$Score = \frac{1 - b(x/x_0)^2}{e^{(x - x_0 - 3a)/a} + 1} \qquad (1)$$

where:

$$x = (ANo * 3 + BNo) * 30 / ABYesNo \qquad (2)$$

and:

- *ANo* - The number of "No" answers at "A" category.
- *BNo* - The number of "No" answers at "B" category.
- *ABYesNo*- - The number of all answers "Yes" and "No", Category "A" and "B".
- *a* = *3*
- *b* = *0.2*
- x_0 = *10*

The above parameters can be modified by the user in order to fit to his/hers project and needs. The numbers and equations are arbitrary, and were found to be appropriate for this case.

2.3.3 The Logic behind the questions

The questions have been chosen to represent common considerations and practice that used at the Hi-Tech industry as well as other industries that reflects the experience of the authors. This Robustool can be adapted and modified by any user to any kind of industry by using his experience and practice.

2.3.4 Examples of the Robustool tables

Tables 2 to 5 show some examples of the long list of questions of the Robustool.

Table 2. Robustness pre - analysis

1	Robustness Pre - Analysis	Present Value	Expanded Value
1.01	Describe over-spec operating uses (Use Cases) and conditions that the system can be exposed to. Choose those of them that the system can be protected from, by reasonable means (as an introduction to Para. 2.01 below)		
1.02	Describe those parameters which can be involved in future upgrades, next generation or new customer's market. Describe these parameters by quantitative values. Upgrades means: expansion of functions, additional functions, additional markets with extreme environmental conditions (The system can be exposed to new markets at Northern Europe and/or Central Africa in which the temperatures are extremely different)		

Table 3. Design Consideration at the Conceptual Design Stage

2	The Criteria	Category	Yes-No-N/A
2.01	The system withstands and is protected against over-spec conditions described at Para. 1.01?	B	Yes
2.02	The concept enables upgrading the system by expanding parameters, which are described at Para. 1.02, without going to re-design? Or, the concept includes, this ability as a provision for.	B	Yes
2.03	The concept is protected by comprehensive patent that can't be easily detoured or blocked by our competitors.	B	Yes

Table 4. Production Consideration at the Conceptual Design Stage

3	The Criteria	Category	Yes-No-N/A
3.01	The concept enables quick detection of defects at production, assembling and testing stages? Examples: Including JTAG in electronic components, test pins on electronic circuits, telemetry software, etc.	B	Yes
3.02	All technologies and components are free of "Single Source" items. Examples: "Back to Square One" can be caused by such a single component which production has been stopped. The same in case of using a new generation of a component that doesn't have FFF compatibility	B	Yes
3.03	The concept is based on long life shelf items, longer than the life of the system itself. In long duration of development it can happen that a brand new component will get obsolete in the process of production or even before it starts	B	Yes
3.04	The concept prevents a miss-mounting (improper order or orientation) that can cause an irreversible damage? Example: Encoding connectors with the same shape but different functions	A	Yes

3	The Criteria	Category	Yes-No-N/A
3.05	The concept does not require special calibrations or adjustments, If it is needed it can be done easily and at the customer's site.	B	No

Table 5. Usage & Maintainability Consideration at the Conceptual Design Stage

4	The Criteria	Category	Yes-No-N/A
4.01	The system is protected against irreversible damage or long shut-down caused by improper operating sequence Examples : Automatic car has to be protected against damage caused by engaging reverse gear while driving forward at high speed , Audio-Tapes have to be protected against damage caused by pressing “Record” button while using a write-protected cassette	B	Yes
4.02	The concept is protected against permanent damage or long shut down caused by activating several functions simultaneously instead of sequentially. Example: Over-load that can causes disengaging by circuit-breaker before burn-out of components occurs	B	Yes
4.03	The concept is protected against permanent damage or long shut down caused by unplanned sudden disconnection from power supply. Examples: Hard disk of a computer can become unreadable by sudden disconnection from mains, UPS is needed. Special delay relays are needed to protect refrigerators and air-conditions against short time of disconnections	B	Yes
4.04	The concept is protected against irreversible damage caused by reverse polarity of DC voltage input, or, improper order of phases at 3-phases power supply Examples: Reverse polarity of DC voltage input can cause burn out of electronic circuits. Improper order of 3-Phases power supply can cause wrong direction rotating of electrical motor that can brake mechanical sub-systems or endanger users.	A	No
4.05	The concept defines self-protection devices that shut down the system before irreversible damage can occur Examples: Self disconnecting electrical motor by Thermo-Switch mounted inside the windings when the motor becomes too hot. Self shut down of computer when the temperature of the CPU excides pre-defined limit.	B	No
4.07	The concept enables useful life of the system without any need to replace parts/subassemblies due to wear or obsolescence. In case that replacement is needed it should be done by simple, short (half an hour max.) operation and at customer site. Examples: Replacing belts of laundry machine, laundry driers, audio-tapes etc.	A	Yes

Table 6. Summary

5	Summary	"Yes" Concept is Robust	"No" Concept is Not Robust
5.01	No. of answers at "A" category	16	1
5.02	No. of answers at "B" category	7	3
5.03	**Concept Robustness Total Score.**	**90**	

The total score has to be evaluated verbally, to emphasize the results of the calculations. Based on practical case studies, and the estimates of experienced designers, the evaluation was set as written in table 7. This score is by no means considered as binding. An experienced designer will always strive to achieve a better robustness evaluation, and the table is considered as a guide only.

Table 7. Robustness Evaluation

Score Range	Robustness Evaluation
87 to 100	The concept is robust
70 to 86	The concept needs some improvements
55 to 69	The concept needs basic improvements
< 55	The concept is definitely not robust

2.4 Test Cases

2.4.1 Fuel System

The design of a control system of fuel supply for a chemical device has been performed by ICDM including the Roobustool. It has been chosen to demonstrate a test case. This system contains 3 programmable firmware components, 4 analog to digital converters with 32 channels, PWM (Pulse Width Modulation) circuits as controlled power suppliers for electrical pumps, high current switches and relays and very high capacitance capacitors as independent reliable energy storage for emergency cases where there is no external power supply.

The functions of this system are: initiating and monitoring sub systems of the chemical device, activating and controlling an electrical pump in close loop, for accurate fuel flow rate, acting as an interface between the main computer of the whole plant and other systems. This system enters autonomously to "Emergency State" by running complicated internal logic, shuts down immediately the fuel supply and activates other safety systems.
By its specification, the system has to be robust and reliable at very high level.

The summary of the results after implementing the Robustool is:
16 answers "Yes" and 1 answer "No" at category "A", 7 answers "Yes" and 3 answer "No" at category "B". The total score was 90 which means that the system is robust.
The only one answer "No" at category "A" is for the question:
"All technologies and components are free of "Single Source" items.

Examples:
"Back to Square One" can be caused by such a single component that its production has been stopped The same in case of start using new generation of a component that doesn't have FFF (Fit Form Function) compatibility "

Most of the programmable firmware components are from single source, without FFF compatibility and in complicated cases the systems, sometimes, are tailored to fit these components. This problem is well known at industry and there is no simple solution. Our system has this disadvantage but there is no effect on functionality.

This high robustness has been approved when this system passed successfully, at the first time, a HALT (Highly Accelerated Life Time) test in which exposing to extreme environmental conditions is the main issue, far out of the formal specifications.

2.4.2 Photofit

The objective of the concept of the second test case is to prevent unwanted persons from entering closed area. The concept is based on photofit - comparing the picture of the person, who wants to enter the closed area, to data bank of pictures of predefined unwanted persons. The robustness of the concept has been evaluated twice, using the Robustool, where sum improvement took place in the concept in between. The results of these evaluations are summarized at Table 8.

Table 8. Robustness Evaluation for Photofit test case

Category	**First Evaluation**		**Final Evaluation**	
	No. of answers "Yes"	**No. of answers "No"**	**No. of answers "Yes"**	**No. of answers "No"**
A	8	2	9	1
B	15	3	17	1
Score	**0.827**		**0.956**	

The answers "No" for category "A" at the first stage of the concept were for the following questions:

2.01 - Can the system withstand and is it protected against over-spec conditions?
4.03 - Is the concept protected against permanent damage or long shut down, caused by unplanned sudden disconnection from power supply?

After some design enhancements, question 4.03 has been eliminated and the total score raised from 0.827, that means that the concept needs some improvements, to 0.965 that shows that the concept is robust.

2.4.3 Threat identification

The objective of the concept of the third test case is to identify persons who carry hidden threats on their body at entrance of closed areas. This concept is based on video camera recording of every person who intend to enter the closed area, image processing of the person's picture, in real time, to identify hidden threats and blocking the gate in case of suspected situations.
The results of the two stages of robustness evaluation are summarized at table 9.

Table 9. Robustness Evaluation for Threat Identification test case

Category	**First test**		**Final Test**	
	No. of answers "Yes"	**No. of answers "No"**	**No. of answers "Yes"**	**No. of answers "No"**
A	6	2	7	1
B	15	2	15	2
Score	**0.782**		**0.916**	

The answers "No" for category "A" at the first stage of the concept was for the following questions:
2.01 - Can the system withstand and is it protected against over-spec conditions?
2.04 - Is the concept based on a unique expert person?

After some enhancements only question 2.04 remained valid and the total score raised from 0.782 that means that the concept needs some improvements, to 0.928 that shows that the concept is robust.

2.4.5 Case studies conclusion

The two case studies shown, were examples from a set of studies that have been performed by 12 teams of graduate students in courses for M.Sc. in Systems Engineering, in the Technion IIT. The participating students were all experienced Systems Engineers. Based on the use of the Robustool in their projects, the participants pointed out that it was a valuable experience and they plan to be using it in their company projects. Each case is unique, therefore statistically proved results are not feasible here, but the general feeling was that the Robustool is a valuable contribution and effective to the design methods of new products.

3 SUMMARY

The Robustool has been used in the development of numerous new products and was found to be a simple, user friendly and powerful tool. By using the Robustool, Designers and System Engineers will be able to attain the followed benefits:

- Obtain the evaluation of the robustness of the product/system by answering a list of questions and if there is a need to do some improvements.
- Obtain guidelines where the improvements have to take place.
- Obtain a quantitative score for the robustness of the product that can play major role in the concept selection at step 9 of the ICDM.
- Use of the Robustool at the conceptual design stage, enables to get a robust design of a product, that will withstand improper use and will be fit for the design of enhancements.

The Robustool is a powerful tool for evaluation of the robustness of a product even at the conceptual design stage, when the full scale development hasn't even started yet.

The Robustool can be used as part of the ICDM methodology or as a stand-alone tool.

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