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# Concurrent multifunction deployment (CMFD)

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## Abstract

Quality Function Deployment (QFD) is a powerful tool for quality planning in product design. In the course of the time, QFD method has passed over several improvements and adaptations to meet specific requests of particular working environments. The current needs and challenges in developing radical innovative and life-cycle optimized products require a concurrent approach of product planning against a complex set of objective-functions (e.g. quality, cost, assembly, manufacturing, environment, technology, service, disposal, etc.). An advanced form of QFD that integrates concepts of concurrent engineering for planning product development with respect to multi-objective-functions is presented in this paper. This framework is called Concurrent Multifunction Deployment (CMFD). TRIZ method was initially exploited to determine the appropriate vectors of intervention in formulating the CMFD methodology. A systematic algorithm supports the CMFD deployment process. It takes into account results from the analysis, innovation and evaluation phases over the product design process, too, ensuring a superior integration of the planning activities within the product development process.

*Keywords: Concurrent planning; Multi-function deployment*

## 1 Introduction

Quality Function Deployment (QFD) is a structured planning and communication methodology that assists organizations during product development process (Akao and Mazur 2003). QFD is a complex and systematic process, consisting of a reunion of methods and means linked by special algorithms that together provide a robust approach by which a multifunctional team identifies and transfers the needs and expectations of the stakeholders through each stage of product development and implementation (Bruce and Chen 2001, Brad 2004). QFD utilizes a series of specialized matrices for interpreting the stakeholders' requirements into the relevant product features, engineering characteristics, manufacturing processes and operations, implementation and disposal aspects, etc. (Al-Mashari *et al.* 2005). QFD requires teamwork and interdependency between different specialists (marketers, designers, production engineers, product management engineers, etc.) (Zheng and Chin 2005). It requires the horizontal integration of those organizational functions that must plan-do-check-act, such as to bring the expressed and un-expressed requirements into the product (Kumar and Midha 2001, Akao and Mazur 2003, Brad 2004, Zheng and Chin 2005, Devadasan *et al.* 2006).

However, as recent studies revealed, classical framework of QFD is not any more suitable to meet the planning needs in product design and development (Chan and Wu 2002, Akao and Mazur 2003, Brad 2004). Products of the future have to be designed in strong connection with their related services (the so-called "extended product"). High levels of technological innovation will have to be incorporated into the next product generations (Carayannis and Coleman 2005). Complex issues related to the whole product life-cycle will have to be taken into account during the planning phase. Embedded intelligence, knowledge, ergonomics, upgradeability, customizability and other high functional product values will have to be carefully planned (Prasad 1998, Bosh and Enriquez 2005). This involves a holistic approach of design, considering the social factors, the environmental factors, the processes, the technologies and the organization in a strong interdependence. So, besides quality, some other objective-functions will have to be taken into account within the design optimization process in order to compete successfully onto the global marketplace. They are related to design for X-ability like: cost, assembly, manufacturing, environment, infrastructure, technology, service, recycling, testing, modularity, etc. In this new framework of competitiveness, quality becomes only a necessary requirement, but not a sufficient one.

When requirements belong to several objective-functions, the deployment process to the production level by means of conventional QFD becomes very difficult. Some of the major barriers in this respect are the followings (Prasad 1998, Kao *et al.* 2002): (a) the QFD matrices are too large and from here inoperable; (b) the time required for successive deployment of huge matrices is too long and the time-to-market become unacceptable; (c) when consider various objective-functions (other than quality) engineers use different tools for optimization – these tools could be less efficient or impracticable under the conventional quality deployment process driven by QFD.

As a consequence, conventional QFD could lead to sub-optimized design when several objective-functions have to be involved. For designing a world-class product, all-important objective-functions concerning to the product life-cycle phases should be included in the equation of design. In order to reduce the cycle time and for better handling of the design process, the deployment of all value-added parameters has to be done in parallel (concurrently / simultaneously) (Prasad 1998, Kao *et al.* 2002, Da Silva *et al.* 2004).

To get robust solutions over the design and development process, for each objective-function the best set of technical characteristics has to be taken into account (also known as critical-to-objective characteristics or performance metrics). The best set of technical characteristics could be different for each objective-function. On the other side, each objective-function will determine different value weights for the same set of technical characteristics. From here, the conclusion that collecting all data in a single QFD frame makes impossible the identification of the value weight that each technical characteristic should bring for better fulfilling each objective-function. Also, the use of a single QFD frame creates difficulties in deploying technical characteristics, because each

technical characteristic should be deployed in a quite different way with respect to each objective-function. More than this, the correlations between technical characteristics could take various nuances in the universe defined by each objective-function. In other words, QFD is a one-dimensional approach that has visible weaknesses with respect to the increasing complexity of products and to the conflicting requirements that have to be handled.

Most of the researches on optimizing the planning process within QFD methodology are mainly focused upon the definition of the appropriate target values of the technical characteristics (from the perspective of conflicts and constraints that occur within the system), upon prioritization of interventions to improve the performances of the technical characteristics, as well as upon the appropriate allocation of financial resources to achieve the performance objectives. In this respect, notable results in terms of optimizing the target values of the technical characteristics are reported in the works of Fung *et al.* (1999), Vanegas and Labib (2001) and Büyüközkan *et al.* (2004), by using fuzzy algorithms, Bai and Kwong (2003), by using genetic algorithms, Chen *et al.* (2004), by using programming models based on fuzzy regression algorithms, as well as latest developments oriented around fuzzy algorithms for value modelling (Chen and Weng 2006, Kahraman *et al.* 2006). In terms of optimizing the financial resource allocation, the reference is given by models based on fuzzy logic and optimal design elements (Fung *et al.* 2002, Tang *et al.* 2002, Gandhinathan *et al.* 2004, Fung *et al.* 2003). For optimizing the prioritization process of the intervention areas in increasing the product competitiveness, elaborated solutions are proposed by Karsak (2004) and by Ramasamy and Selladurai (2004), by means of techniques of multi-criteria analysis and fuzzy logic algorithms. However, when several objective-functions have to be concurrently deployed, there is no very much benefit from these contributions. Some further works, like those of Adiano and Roth (1994), Chan and Wu (2002), Kao *et al.* (2002), Akao and Mazur (2003), Zheng and Chin (2005), bring only minor contributions around the issue of concurrent planning in QFD. It is however the merit of Prasad (1998) on highlighting for the first time the importance of concurrent approach in QFD. Prasad (1998) also proposed an embryonic concept called Concurrent Function Deployment (CFD), but CFD does not give a practical and comprehensive view on how to deploy the objective-functions to lower levels (operational levels) and how to integrate planning processes with other design processes. Importance of integrating product planning (e.g. QFD) with innovation (e.g. TRIZ) and experimental robust design (e.g. Taguchi) issues is more and more highlighted by various works (e.g. Terminko 1997, Yamashina *et al.* 2002). However, this integration is treated only in relation with the House of Quality (HOQ) and it does not take into account the case of concurrent planning of multiple objective-functions.

This paper attempts to set up a comprehensive framework for multi-stage concurrent planning of multiple objective-functions within a QFD-based philosophy. This framework is called Concurrent Multi-Function Deployment (CMFD) and it is scientifically incepted by means of TRIZ method. Further, a set of foundation pillars for CMFD are formulated. Based on the inventive vectors extracted from TRIZ and on the foundation pillars, the paper continues with the formulation of the CMFD algorithm and ends with an example and recommendations for practical implementation.

## 2 Inventive vectors of intervention

In order to set up a reliable framework for concurrent multifunction deployment, this paper proposes an innovative approach for concept formulation. It starts with the identification of performance requirements related to the CMFD framework. Afterwards, the conflicting problems are identified by means of the TRIZ method (Altshuller 2000). Based on TRIZ algorithm, appropriate vectors of intervention are established. The set of vectors of intervention provides only guidelines about the “universe” where solutions should be formulated, rather than proposing solutions to the identified contradictions. However, using TRIZ better results can be obtained during solution synthesis process.

The application of TRIZ for this problem reveals the following pairs of conflicting problems: (CP1) need of small-size QFD matrices versus complexity of the deployment process;

(CP2) fast deployment from one phase to the next one versus quality of required information; (CP3) possibility to use various tools for planning along the deployment lines versus uniformity of the deployment algorithm; (CP4) integration of as many as possible objective-functions versus complexity of the deployment process; (CP5) possibility to use customized technical characteristics for each objective-function versus complexity of the planning process; (CP6) need to link concurrently the deployment lines (overall concurrent approach of the deployment) versus serial deployment along each objective-function; (CP7) ensuring an optimal overall planning versus ensuring optimal planning against each objective-function. In terms of TRIZ engineering parameters (Altshuller 2000), the problems here presented can be reformulated as: (EP1) surface of the static element (6) versus complexity of the system (36); (EP2) speed of the process (9) versus loss of information (24); (EP3) system adaptability (35) versus convenience during operation (33); (EP4) volume of the moving system (7) versus harmful side effects (31); (EP5) accuracy of system development (29) versus productivity (39); (EP6) waste of time (25) versus accuracy of performance measurement (28); (EP7) strength of the system (14) versus harmful side effects upon the system (31). Numbers in brackets represent the corresponding TRIZ engineering parameters as mentioned in the specific literature (Altshuller 2000).

Introducing the conflicting problems within the TRIZ matrix of contradiction and using the set of TRIZ inventive principles (Altshuller 2000), the vectors that define the universe of intervention for conceptualizing the CMFD framework are revealed. They are presented in table 1, together with possible practical solutions.

‘[insert table 1 about here – see table 1 at the end of the body text]’

Table 1. Inventive vectors of intervention and possible related practical solutions.

The results from table 1 are used for the foundation of the CMFD algorithm. Beside this, a set of statements that come up from practice have to be taken into account. They are further described in the next section of this paper.

### 3 Key aspects for the foundation of concurrent multifunction deployment

To increase the reliability of the CMFD framework, some key aspects that have been empirically identified over time by practitioners should be also considered. They are presented in the form of 6 problem statements.

#### 3.1 Problem statement 1

A percentage of 60% to 95% of the total product cost is determined during the initial design stage (e.g. Adiano and Roth 1994, Terminko 1997). Because of this, optimal solutions should be defined very early in the design process (concept of the architecture and concept of sub-systems / mechanisms). To this, failure analysis should to be integrated within the concept generation phase of the product, as well as immediately after this phase. Tools like System-FMEA could be very useful in this respect.

#### 3.2 Problem statement 2

For preventing the occurrence of failures in product design due to some later constraints coming up in the production process planning stage, it is necessary that product planning stage and at least a portion of the process planning stage to be performed simultaneously. Process planning cannot be completely carried out as long as the design is not well-defined at the piece level. Portion of the production planning could be also worked out simultaneously with product and process planning, if necessary.



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**3.3 Problem statement 3**

When optimize a system with respect to several objective-functions (multi-criteria, multi-purpose optimization), the boundaries (or constrains) of the space have to be well-known before formulating the optimization problem.

**3.4 Problem statement 4**

The optimal solution of a system with respect to a given criterion will not be generally the same with the optimal solution of the same system with respect to another given criterion. Extrapolating, it can be said that the optimal solution of a system with respect to a set of criteria might be quite different than the optimal solutions of the respective system relative to each of those criteria when they are considered independently. Usually, in practice, each objective-function is expressed by a different category of stakeholders. According to Arrow’s impossibility theorem, when the whole set of objective-functions is considered, the overall optimal solution could look sub-optimal when it is analyzed independently by each category of stakeholders. So, the use of averaged preference data seems not being the best choice when attempt to optimize the product design. However, countless reports show that for real, complex products the implications of the Arrow’s impossibility theorem only manifest themselves to a small extend, lowering the optimality of the overall design, but not at the level it becomes inappropriate. With respect to this issue, an effective preventive action could be the following: (a) define firstly, by applying a simultaneous approach, the optimal solution with respect to each criterion (objective-function) at the level of architectural design and sub-system / mechanism design (where 60% to 95% of failures occur); (b) define the overall solution considering the already known “boundaries” from stage (a) in connection with specific tools of inventive problem solving (e.g. TRIZ). When applying this philosophy, the risk of lowering the optimality for the overall design could be minimized.

**3.5 Problem statement 5**

In practice, data and information about each objective-function are usually collected independently and manipulated by teams that are normally specialized in that topic. For reducing the cycle-time, it could be useful that product planning to be performed simultaneously with respect to each objective-function, by specialized workgroups. This approach could be also justified by the fact that some of the objective-functions are independent or almost independent from each other (Prasad 1998).

**3.6 Problem statement 6**

The deployment of requirements can be done directly to the level of parts, processes or production without passing through some other intermediary phases. The serial deployment of requirements, as in the classical Clausing four-phase QFD model (Chan and Wu 2002), is artificial because the results at a lower level of deployment are not changed qualitatively (and should not be changed quantitatively, too) indifferent how many deployments are in between the top-level design and the currently analysed level. Detailing the system on more levels is because the designer has an interest to get more information about that system, not because of increasing the accuracy of the deployment process. This is very true because deployment is not design. For example, parts are defined not as a result of the stakeholder-requirements deployment process but as a result of the design process. This means that parts cannot be defined as long as the product architecture and mechanisms are not designed. Deploying firstly the requirements at the level of product architecture will help without doubt engineers for better defining product’s parts, but part-design stage is previously done to part-deployment stage. As a consequence, part-deployment has no effect on the value weights that parts have in fulfilling requirements. In this context, deploying parts is simply only a solution-analysis process at the part level and not a solution-synthesis process. In conclusion,

the design at lower levels could be influenced by the results of the deployment process at upper levels, but the deployment at lower levels has no effect on the design and deployments at upper levels. Because of this reason, concurrent deployment is possible.

#### 4 The algorithm of concurrent multifunction deployment

Recommendations from table 1, in combination with the problem statements mentioned in the previous section, led to the formulation of a comprehensive methodology for concurrent multifunction deployment that has a high potential for natural integration within the framework of the design process specific to new, highly innovative and complex products. There is mainly a creative process rather than a formalized one in exploiting the recommendations from table 1 to elaborate the CMFD framework. This means that the CMFD framework could have several reliable paths. The reliability of a certain path is given by the level of satisfaction of the vectors of intervention and **the related generic solutions (scientifically determined in table 1)**. For a better assimilation into practice, the CMFD framework has the form of a set of steps. This organization allows a higher flexibility in making the CMFD planning framework more interactive with some other specific frameworks within the design process (e.g. analysis, innovation, evaluation, decision-making, design, testing, etc.).

##### **4.1 Step 1: Define the set of objective-functions and organize specialized teams for each objective-function**

The decision making team will define, according to the development strategy over the product life-cycle, which is the necessary and sufficient set of objective-functions that, if fulfilled, will contribute to a long-term competitive advantage of the product onto the market. For example, a set of objective-functions could be: {design for quality; design for minimum cost; design for testing; design for manufacturing & assembly; design for easy service; design for dependability; design for de-assembly}. If there are considered  $n$  objective-functions, symbolized with  $OF_1, \dots, OF_n$ , they form a set of objective-functions denoted with  $SOF$  and expressed as:

$$SOF = \{OF_1, OF_2, \dots, OF_n\}. (1)$$

It is a key issue at this step to have a good understanding about the major aspects of product life-cycle and about the major aspects of product competitiveness in order to define the necessary and sufficient set of objective-functions. Too many objective-functions could harm the development process in terms of time, cost, as well as overall competitive performance.

The project manager will define a feature team for each specified objective-function according to their qualification and experience. Concurrent approach of several objective-functions seems to involve a quite large number of people. This might happen, but there is no constrain to have people from a certain team working in the same time within some other teams. Association of a feature team to a certain objective-function does not mean that this team is rigid and has no communication with the other teams. By contrary, feature teams are encouraged (quite forced) to communicate during each deployment stage and at the termination of each deployment stage as effective and efficient as possible, throughout various means (Intranet and Internet-based conferences, face-to-face meetings, common knowledge base, etc.). This approach is part of the concurrent engineering philosophy, too.

##### **4.2 Step 2: Identify and rank business related requirements and objective-function related requirements**

In order to solve properly possible conflicts between the objective-functions, they should be firstly evaluated against the business objectives of the company for the specified project. In this respect, a feature team will determine and rank the business requirements, too. If there are denoted



with  $BR_1, \dots, BR_m$  the business requirements and with  $U_1, \dots, U_m$  their relative importance, the constitutive set of these requirements, denoted with  $SBR$ , could be expressed under the form:

$$SBR = \{BR_1[U_1], \dots, BR_m[U_m]\} . (2)$$

Business requirements refer to strategic issues of the company, including both financial and non-financial aspects. The ranking process could be elegantly performed by means of the ANP method (Büyüközkan *et al.* 2004).

Each feature team will determine and rank the necessary and sufficient requirements that characterize the objective-function to which the feature team was assigned. This task is performed simultaneously by all feature teams. During this operation, feature teams should communicate each other for shearing information, as the concurrent engineering philosophy encourages. The communication process is necessary for a better systematization of information and for avoiding redundancies. Requirements will be further ranked. There is no special restriction on how to perform this process. Each team will decide on the best variant, according to the local context. If there are denoted with  $RC_{ij}$ ,  $i = 1, \dots, n$ ;  $j = 1, \dots, k_i$  the requirements determined by the feature teams, where  $k_1, k_2, \dots, k_n$  is the number of requirements established for each objective-function  $OF_1, OF_2, \dots, OF_n$  and with  $R_{ij}$ ,  $i = 1, \dots, n$ ;  $j = 1, \dots, k_i$  the degrees of importance of each requirement, the sets of pairs ‘requirements-degrees of importance’, could be formulated as in (3).

$$\left\{ \begin{array}{l} \{RC_{11}[R_{11}], \dots, RC_{1k_1}[R_{1k_1}]\} \\ \dots \\ \{RC_{i1}[R_{i1}], \dots, RC_{ik_i}[R_{ik_i}]\} \\ \dots \\ \{RC_{n1}[R_{n1}], \dots, RC_{nk_n}[R_{nk_n}]\} \end{array} \right\} . (3)$$

The representation from (3) is useful for simplifying the explanations in the next steps of the CMFD framework.

#### 4.3 Step 3: Plan the objective-functions

The set of objective-functions will be then analyzed against the set of business requirements defined at step 2. A QFD approach will be used in this respect. Ranking the objective-functions relative to strategic goals helps in formulating the overall solution of the product and for solving properly potential conflicts during the planning and design processes. This step is suggestively illustrated in figure 1, where  $F_1, \dots, F_n$ , are the value weights of the objective-functions and  $C_{ji}$ ,  $j = 1, \dots, n-1$ ;  $i = 2, \dots, n$ ,  $i \neq j$  is the correlation coefficient between the objective-function  $j$  and the objective-function  $i$ ,  $i \neq j$ . Correlations between objective-functions could be positive, negative or none and they could have different strengths.

‘[insert figure 1 about here – see figure 1 at the end of the body text]’

Figure 1. Analysis of the objective-functions against the business requirements.

#### 4.4 Step 4: Determine and rank value characteristics for each objective-function

Each feature team will define the set of value characteristics for each objective-function. During this process, all teams will communicate each other in order to shear good ideas. Value characteristics are those characteristics that ‘translate’ requirements into engineering specifications. Value characteristics are quantifiable, measurable metrics of the technical solutions. Value characteristics are denoted with  $VC_{ij}$ ,  $i = 1, \dots, n$ ;  $j = 1, \dots, t_i$ , where  $t_i$ ,  $i = 1, \dots, n$ , is the number of

value characteristics for the objective-function  $i$ . Applying the QFD-type approach for value weight determination (e.g. Akao and Mazur 2003), each value characteristic is weighted. The value weights are denoted with  $W_{ij}$ ,  $i = 1, \dots, n$ ;  $j = 1, \dots, t_i$ , where  $t_i$ ,  $i = 1, \dots, n$ , is the number of value characteristics for the objective-function  $i$ . The sets of value characteristics have to be analyzed from various points of view (value weights, types and levels of correlations, relationship levels, etc.).

#### 4.5 Step 5: Generate local solutions for the overall system architecture and its constitutive subsystems

For each objective-function the corresponding feature team will generate solutions for the overall system architecture, as well as for the constitutive mechanisms, using as inputs the value characteristics defined in the previous step for the respective objective-function. This task is actually related to the design process rather than to the planning process. Feature teams could use approaches and tools they consider most accessible and affordable to the given context (the consideration of best practices for solution generation is however encouraged). Even so, this step is led by the results from step 4. Step 5 is required for further product planning.

At the end of this step,  $n$  variants of the overall system architecture and of the constitutive subsystems (mechanisms) are generated. Each of the  $n$  variants is linked to a certain objective-function and theoretically speaking, each variant should be optimal with respect to its corresponding objective-function. These variants will be further used as references for generating the complete overall solution. The idea within the CMFD method to design locally optimized solutions as inputs for designing the overall solution (see step 7) represents an effective design approach when complex sets of requirements are taken into account in product development.

Step 5 is run simultaneously by all feature teams. Communication between teams is encouraged, such as all good ideas to be sheared at the right time. Here, both the overall system architecture and the corresponding mechanisms are generated concurrently, without any QFD-related deployment of the characteristics that define the overall system architecture to the level of mechanisms. This kind of approach is recommended because mechanism planning cannot be done selectively. Each characteristic that defines the overall system represents an item that must be solved. Overall system architecture represents, in fact, the top-level design of the overall system. A top-level design leads to the generation of the first-order sub-systems (which are only a few). Deploying value characteristics through these few abstract sub-systems (black-boxes) for supporting the design process of mechanisms does not mean very much, that is, the benefits due to this deployment cannot compensate the time and effort consumed to run it. In this context, it is justified only the deployment of the value characteristics through the mechanisms for further supporting the process of part definition.

#### 4.6 Step 6: Plan the local variants

This step consists in deploying the value characteristics defined at step 4 into product sub-systems. This means that  $n$  QFD-type matrices are formulated. The deployment of all matrices is done simultaneously. At the end of this stage, each set of mechanisms of each variant will be weighted against the value characteristics that correspond to the respective variant. The process is illustrated in figure 2.

[insert figure 2 about here – see figure 2 at the end of the body text]

Figure 2. Deploying concurrently the local variants (designed at mechanism-level).

In figure 2, product variants are represented as a combination of mechanisms. They are symbolized according to the following relationship:

Variant  $i = (M_{i1} * M_{i2} * \dots * M_{ih_i}), (4)$

where  $i, i = 1, \dots, n$ , is the index of the  $i$ -th variant;  $n$  is the number of variants;  $M_{ij}, i = 1, \dots, n; j = 1, \dots, h_i$ , is the  $j$ -th mechanism of the  $i$ -th variant;  $h_i, i = 1, \dots, n$ , is the number of mechanisms of the  $i$ -th variant;  $*$  is a symbol showing that between the constitutive mechanisms there are various kinds of relationships. The corresponding value weights are denoted with  $Y_{ij}, i = 1, \dots, n; j = 1, \dots, h_i$ . The planning process of the local variants effectively shows the ‘multiple’ facets of the same system. It reveals the differences in relevance of the mechanisms for the same system when it is placed in different contexts. This step actually brings to live one of the most important properties of complex systems: in a complex world there is no single best solution – otherwise the problem would not be considered complex. Besides this, results from step 6 are very useful for value engineering within the new product. The value weights of product mechanisms (sub-systems), calculated at this step, give a perspective about the relative costs that are justified to spend on producing each mechanism. For example, if the cost objective to produce a given product  $P$  is  $CO$ , the maximum justified costs to produce the mechanism  $M$ , which has the value weight  $Y[\%]$ , is  $CO \cdot Y$ . This effectively acts as ‘economic constrain’ during part design process. If a certain mechanism is met in several local variants (which is very probable, because teams communicate each other during step 5), there is a very high probability the respective mechanism to have different impacts in each local variant where it is taken into consideration. On this way, engineers have a better view about the roles the respective mechanism has in the equation of competitiveness for the overall solution. This information is very helpful during step 7 of the CMFD method, when possible conflicting points of view and compromise-related decisions are met.

4.7 Step 7: Generate the complete overall solution by aggregation and innovation

In order to generate the complete overall solution as an aggregated result of the local solutions (the set of  $n$  local variants), a specific working algorithm is required. This paper proposes an aggregation algorithm in 4 stages.

Stage 1: Identify the objective-function having the highest value weight. Information from step 3 is taken into account as input data. The objective-function with the highest value weight will be considered the starting point in the working algorithm. If  $F_{\max}$  denotes the maximum value weight, the following relationship comes up:

$F_{\max} = \max \{F_1, F_2, \dots, F_n\} . (5)$

It is further symbolized with  $POF$  the objective-function having the highest value weight in the set of  $n$  objective-functions.

Stage 2: Group the other objective-functions relative to  $POF$ .  $POF$  is correlated with the other  $n-1$  objective-functions in various ways: positive correlations, negative correlations or no correlations, as well as at various strengths (see figure 1). The type of correlation between two objective-functions is determined by the correlations between their constitutive requirements. In this respect, the rest of the  $n-1$  objective-functions can be sorted on three categories: the group of those objective-functions that are positive correlated with  $POF$ , the group of those objective-functions that are not correlated with  $POF$  and the group of those objective-functions that are negative correlated with  $POF$ .

Stage 3: Order the objective-functions in each of the three groups. Considering that the  $POF$  is the  $k$ -th objective-function in the matrix from figure 1, for the objective-functions that are positive or negative correlated with  $POF$  will be calculated an index, denoted with  $H_j, j = 1, \dots, n, j \neq k$ , as the product between the value weight  $F_j, j = 1, \dots, n, j \neq k$  and the correlation coefficient  $C_{jk}, j = 1, \dots, n, j \neq k$ . This formula is shown below:

$$H_j = F_j \cdot C_{jk}, j = \overline{1, n}, j \neq k, C_{jk} \neq 0. (6)$$

In the group of objective-functions that are positive correlated with *POF*, the objective-functions will be ordered starting with the one having the highest *H* and ending with the one having the lowest *H*. The same rule is kept for the group of objective-functions that are negative correlated with *POF*. It is highlighted the fact that  $C_{jk} < 0$  in the group of negative correlated objective-functions, so the one with the highest *H* will have the lowest magnitude in absolute value, too. The objective-functions that are not correlated with *POF* will be ordered starting with the one having the highest value weight *F* and ending with the one having the lowest value weight *F*.

*Stage 4: Generate the complete overall solution using an iterative approach.* The complete overall solution will result as a ‘compromise & combination’ of the set of *n* local solutions. In this respect, the following rule will be applied:

(a) The solution corresponding to the *POF* will be taken and analyzed together with the solution corresponding to the first objective-function in the group of the objective-functions that are positive correlated with *POF*. Because the two objective-functions are positive correlated, the best ideas from the local solutions will be combined, resulting an improved hybrid solution. The two feature teams that have been responsible for generating the two local solutions will work together to achieve this goal. During this process, the two feature teams could use various tools for selection and analysis.

(b) The hybrid solution from (a) will be then analyzed against the local solution corresponding to the second objective-function in the group of the objective-functions that are positive correlated with *POF*. Representatives from three feature teams will work out the new variant, as a combination of the best ideas from the hybrid solution generated at phase (a) and from the current local variant.

(c) The process will go on in the manner above described until all objective-functions from the group of objective-functions that are positive correlated with *POF* are consumed. After that, the group of no correlated objective-functions is taken into account and the process is continued until all of these objective-functions are consumed. At the end, the group of objective-functions that are negative correlated with *POF* will be taken into account. Because at this phase potential conflicts could occur, they have to be solved without compromise, if possible. In this respect, it is firstly required to identify pairs of conflicting problems between the compared variants. Afterwards, innovative solutions have to be formulated. Methods like TRIZ could offer a real support in this respect. At the end of this process, the complete overall solution (in terms of system architecture and constitutive mechanisms) will be defined. The group of steps 5, 6 and 7 represents a novel approach in complex product planning and clearly differentiates the CMFD framework with respect to other methods of concurrent deployment like, for example, the CFD method (Prasad 1998).

#### 4.8 Step 8: Analyze the complete overall solution against value characteristics

Step 8 is another novelty introduced by CMFD in product planning deployment process. The overall solution defined at step 7 is analyzed with respect to the value characteristics corresponding to each objective-function. All feature teams have to perform this task simultaneously. A QFD-type approach is applied in this case, too. This step is illustrated in figure 3, where the constitutive mechanisms of the complete overall solution are denoted with  $M_j, j = \overline{1, \dots, q}$ , with *q* symbolising the total number of mechanisms. Applying the QFD procedure, the value weights of the mechanisms with respect to each objective-function are determined. They are denoted with  $E_{ij}, i = \overline{1, \dots, n}, j = \overline{1, \dots, q}$ . A good design is when along each row and along each column of each relationship matrix from the QFD framework exists at least a strong relationship. In order to define the overall value weight of each mechanism, the following rule is applied:

(a) Normalize to 1 the value weights of the objective-functions. The following formula will be used in this respect:

$$FN_j = \frac{F_j}{\sum_{k=1}^n F_k} = \frac{F_j}{100}, j = \overline{1, n}, (7)$$

where  $FN_j, j = 1, \dots, n$ , is the normalized value weight of the  $j$ -th objective-function when  $F_j, j = 1, \dots, n$ , are expressed in percentages ( $F_1 + \dots + F_n = 100$ ).

(b) Determine the overall value weights of the mechanisms. The following formula will be used in this respect:

$$E_k = \sum_{j=1}^n FN_j \cdot E_{jk}, k = \overline{1, q}, (8)$$

where  $E_k, k = 1, \dots, q$ , is the overall value weight of the  $k$ -th mechanism.

‘[insert figure 3 about here – see figure 3 at the end of the body text]’

Figure 3. Analysis of the complete overall solution with respect to each objective-function.

#### **4.9 Step 9: Define the constitutive parts of the complete overall solution and the processes that support part manufacturing**

Representatives from all feature teams will detail the overall solution to part level and will define the key properties of the parts. Key properties of parts are actually defined by the group of the most important characteristics of the parts that are critical to meet value characteristics of the product. Concurrently, they will also define the production processes, as well as will define the key process properties. Key process properties are actually defined by the group of the most important characteristics of the production process that are critical to meet value characteristics of the product. Optional, if the complexity of the product effectively requires, at step 9, a supplementary deployment could be performed: outputs from step 8 to be deployed into product parts, for part value analysis. Having established a cost objective, the calculation of the value weights for parts reveals how much value incorporates each product part. This is a measure of the quality of product mechanisms' design.

#### **4.10 Step 10: Plan concurrently parts and their corresponding processes**

Part properties and process properties will be concurrently analyzed with respect to each set of value characteristics that define the objective-functions. It might be possible that some of the value characteristics to have no relevance at this stage (actually, those value characteristics that are only related to product concept design). This step represents another contribution of the CMFD method to concurrent product planning. It is shown in figure 4, where with  $PP_j, j = 1, \dots, g$ , are denoted the part properties,  $g$  being the number of part properties and with  $RR_k, k = 1, \dots, s$ , are denoted the process properties,  $s$  being the number of process properties. The local value weights of part and process properties are denoted with  $K_{jf}, f = 1, \dots, n, j = 1, \dots, g$ , respectively with  $L_{fk}, f = 1, \dots, n, k = 1, \dots, s$ . The overall value weights of part and process properties will be calculated as:

$$K_j = \sum_{f=1}^n FN_f \cdot K_{jf}, j = \overline{1, g}, (9)$$

$$L_k = \sum_{f=1}^n FN_f \cdot L_{fk}, k = \overline{1, s}, (10)$$



where  $K_j, j = 1, \dots, g$ , is the overall value weight of the  $j$ -th part property and  $L_k, k = 1, \dots, s$ , is the overall value weight of the  $k$ -th process property.

[insert figure 4 about here – see figure 4 at the end of the body text]

Figure 4. Planning concurrently parts and processes.

#### 4.11 Step 11: Plan the manufacturing operations

This last step is another original contribution of CMFD to enhance the quality of product planning process. Each manufacturing operation is related to a set of key manufacturing parameters (examples: turning speed, air pressure level, pressing force, cutting depth, exposure time, etc.). The whole set of key manufacturing parameters of all manufacturing operations will be planned both in terms of part properties and process properties. The value weights will give a perspective about the level of detailing the quality assurance plans with respect to each operation, in order to keep under control the production processes. Considering a number of  $w$  key manufacturing parameters,  $OP_1, \dots, OP_w$ , their resulted value weights will be denoted with  $Z_1, \dots, Z_w$ .

Each constitutive part of the overall solution will be analyzed against the whole set of key manufacturing parameters. Considering the system having a number of  $p$  parts, it will be defined a degree of difficulty  $D_{rt}$  in manufacturing the part  $r, r = 1, \dots, p$ , with respect to the key manufacturing parameter  $t, t = 1, \dots, w$ . The following scale could be used for defining the degree of difficulty: 0 – if no connection exists between the part  $r$  and the manufacturing parameter  $t$ , 1 – if the difficulty is low, 2 – if the difficulty is moderate, 4 – if the difficulty is high and 7 – if the difficulty is very high. The difficulty in manufacturing a part by means of a certain operation is lower or higher depending on the way the part is designed. A good design in terms of manufacturing operations will lead to better quality. In order to define the quality of part design, a mark  $Q_r, r = 1, \dots, p$ , will be given to each part, using the following formula:

$$Q_r = \sum_{t=1}^w D_{rt} \cdot Z_t, r = \overline{1, p}. \quad (11)$$

For the whole set of parts, a global mark  $Q$  can be calculated. It represents the sum of the marks given to the parts:

$$Q = \sum_{r=1}^p Q_r. \quad (12)$$

A lower value of  $Q$  means a better design of the overall solution in terms of manufacturing. If a relevant number of parts have  $D_{rt}$  of value 4 or 7 it is required going back to step 9. In redesigning the parts, engineers have to look on reducing the number of operations related to each part, on reducing the number of parts and on reducing the difficulty in manufacturing the part using the available production processes. Using the mark  $Q$ , engineers will have the possibility to evaluate the level of improvement.

#### 5 Illustrative example

In order to highlight the way CMFD method could be used in practice, an illustrative example is further introduced. For the easiness of understanding, a simple, well-known product is considered: the pencil. For this project, the following set of objective-functions has been selected (see step 1 of the CMFD method):

$$SOF = \{high\ quality, high\ reliability, meet\ safety\ requests, minimum\ cost\}. \quad (13)$$

For the company XYZ that manufactures pencils, business related requirements and their importance are formulated by the management board, based on business ambitions and various market surveys (see step 2 of the CMFD method). For the simplicity of this case study, three business-related requirements have been selected:  $BR_1$  – to address both to pupils, students, specialists and usual people [ $U_1 = 60\%$ ];  $BR_2$  – to address to various cultural trends and / or traditions [ $U_2 = 30\%$ ];  $BR_3$  – to induce / influence more people in using pencils in an age when pens and computers & printers are strong substitutes [ $U_3 = 10\%$ ].

For each objective-function, a team of specialists is set up. Each team formulates and ranks the requirements related to the corresponding objective-function (see step 2 of the CMFD method). For the purpose of this case study, only a limited number of key requirements have been selected. Results are shown in table 2.

‘[insert table 2 about here – see table 2 at the end of the body text]’

Table 2. Objective-function related requirements and their relative ranks.

The weighting process of objective-functions is illustrated in figure 5 (see step 3 of the CMFD method). In figure 5, as well as in the other figures where symbols are used to express the relationship levels, their numerical equivalences are:  $X \equiv 9$ ,  $B \equiv 3$ ,  $A \equiv 1$ . According to results in figure 5, the objective-function ‘minimum costs’ is negative correlated with the other three objective-functions. In terms of value weight, there are close impacts of the objective-functions to meet business objectives, with a relative differentiation for the objective-function ‘high quality’.

‘[insert figure 5 about here – see figure 5 at the end of the body text]’

Figure 5. Planning matrix of objective-functions.

For each objective-function, a set of product value characteristics is defined. These sets are built up by the feature teams. They are further ranked by means of QFD-type matrices (see step 4 of the CMFD method). Results are presented in figure 6, figure 7, figure 8 and figure 9. It is revealed that, the same product generates differences in value characteristics with respect to different objective-functions. Also, similar value characteristics have different value weights with respect to different objective-functions (e.g. length).

‘[insert figure 6 about here – see figure 6 at the end of the body text]’

Figure 6. Planning matrix of value characteristics related to objective-function ‘high quality’.

‘[insert figure 7 about here – see figure 7 at the end of the body text]’

Figure 7. Planning matrix of value characteristics related to objective-function ‘high reliability’.

‘[insert figure 8 about here – see figure 8 at the end of the body text]’

Figure 8. Planning matrix of value characteristics related to objective-function ‘meet safety requests’.

‘[insert figure 9 about here – see figure 9 at the end of the body text]’

Figure 9. Planning matrix of value characteristics related to objective-function ‘minimum costs’.

The local solutions proposed by the feature teams with respect to each objective-function are revealed in figure 10 (the hand sketch of the whole assemble) and figure 11 (the hand sketch of the main sub-systems) (see step 5 of the CMFD method). From technical point of view, the process of solution generation is outside the CMFD framework. Engineers can use any methodology to fulfil this issue; only the final results from this process are relevant for the CMFD method. Figure 10 shows the sketches of the solutions proposed by teams with respect to the objective-functions (from left to right: high quality, high reliability, meet safety request and minimum costs). Each of the four solutions tries to fulfil as much as possible the requirements expressed by the corresponding objective-function. Because teams have communicated each other during the concept development process, the mechanisms for the first three solutions are quite similar, with some slight differences, because the three objective-functions, that is, high quality, high reliability and meet safety requests, are positive correlated, so any good idea expressed by one team can be exploited by the other teams. Differences to the first three solutions occur in terms of shapes of the body, material used to manufacture various components, sizes of components, textures of the external surface, as well as concepts of the interfaces between sub-systems. For example, the first solution, besides issues related to ergonomics and quality of the graphite (lead), focuses more on aesthetics than solutions two or three. Also, the second solution considers some of the parts, including the external body, being manufactured from metallic alloys to enhance the reliability issues. The third solution considers special shapes and sizes of the body, as well as of the material of the body to increase the safety issues. Lasting of the pencil tip, as well as the quality of the tip is solved by adopting the principle of 'automatic' pencils. The control of the tip's length is provided with similar concepts of the specific mechanisms for the first three solutions. However, the solution related to high reliability takes more care on this issue and uses in this respect metallic components that are able to adjust more accurately the tip's length than solutions one and three (in the detriment of costs), which use only plastic components for the feeding mechanism. The last solution, related to minimum costs, differs dramatically with respect to the first three solutions. It is actually the classical wooden pencil, with a rounded body surface. To increase the lasting period of the classical pencil, the length of its body is longer. Actually, these 'tangible' differences revealed by the local solutions are the drivers for innovation during the design process of the overall solution. This is one of the major contributions of the CMFD method: to link effectively the product planning process to technical product innovation.

[insert figure 10 about here – see figure 10 at the end of the body text]

Figure 10. Local solutions (hand sketches of assembles): from left to right – quality, reliability, safety, costs.

[insert figure 11 about here – see figure 11 at the end of the body text]

Figure 11. Local solutions (hand sketches of sub-systems): from left to right – quality, reliability, safety, costs.

Local solutions are further planned with respect to value characteristics (see step 6 of the CMFD method). Inputs into the deployment process are the value characteristics and their ranks, as obtained during step 4 (see figures 6 to 9). The outputs of the deployment process are the mechanisms of each of the four solutions and their corresponding value weights. Because of the limited space for the paper, the graphical representation of the relationship matrices is not here included (it actually consists of four matrices that look like those in figures 6 to 9). The outputs of the deployment process are presented in table 3. For the case study under consideration, the first three solutions have somehow similar mechanisms, with slight differences. To highlight these slight differences, they have been denoted as concept A, concept B and concept C in table 3. The fourth solution is radically different to the first three solutions and will lead to many challenges during the final concept definition (see the aggregation phase in step 7 of the CMFD method).

[insert table 3 about here – see table 3 at the end of the body text]

Table 3. Sub-systems for local solutions and their relative value weights.

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Results in table 3 reveal variations of the impact (value weight) each mechanism has with respect to various objective-functions. As it was explained in section 4.6, this information is extremely important for the design engineers because, having established a cost objective, they can verify the feasibility of their design from production costs point of view even from the early stages of the development process (product concept definition). If the estimates show some drawbacks from costs perspective, engineers can redefine the respective solution in duty time and within budget. The information about value weight is also relevant during the aggregation process in the step 7, stage 4, of the CMFD method, where engineers have to decide which from several proposed solutions of a given mechanism will be chosen for the final concept. The best case is when the final concept of the respective mechanism can integrate the properties of all local solutions (because each local solution better fits to a certain objective-function). This involves innovation, otherwise compromise can be easily done based on value weight analysis – the local concept having more relevance for a given objective-function will have priority into the final concept. For example, considering the sub-system ‘body’, results in table 3 tell that the concept related to ‘safety requests’ (41.1%) has priority in front of the other concepts; the second place is taken by the concept related to ‘reliability’ (28.0%), closely followed by the one related to ‘minimizing costs’ (24.1%) and lastly by the one related to ‘high quality’ (13.9%). For the sub-system ‘lead pushing-out mechanism’, either the concept related to ‘quality’ or ‘safety’ can have priority into the final concept, etc.

The elaboration of the final concept requires following the algorithm proposed at step 7. The first stage consists in determining the objective-function with the highest rank. The ‘high quality’ is the *POF* in this case (see figure 5). The second stage requires grouping the other objective-functions based on the correlation characteristics with *POF*. For this case study, only two groups are revealed. Group 1 includes the objective-functions that are positive correlated with *POF*; in this case it is about ‘high reliability’ and ‘meet safety requests’. Group 2 includes the objective-functions that are negative correlated with *POF*; in this case it is only about ‘minimizing costs’. The third stage requires ordering the objective-functions in each group considering the coefficient *H*. According to this, in group 1 the first position is held by ‘high reliability’ (see figure 5 and relationship (6):  $H = 23.1 \cdot 3$ ,  $++ \equiv 3$ ) and the second position is held by ‘meet safety requests’ ( $H = 22.4 \cdot 3$ ). The second group has only one objective-function, so its position is obvious. The fourth stage relates with the aggregation of local solutions into the overall solution. According to the algorithm, firstly the concept related to ‘high quality’ and ‘high reliability’ will be aggregated. The hybrid solution will be further aggregated with the concept related to ‘meet safety requests’. The result will be further aggregated with the concept related to ‘minimizing costs’. For this last aggregation, innovation is encouraged because negative correlations occur. TRIZ method or some other tools for inventive problems solving could be considered in this respect (e.g. ASIT, USIT). For the case study here presented, the first aggregation generates a hybrid *HA* that includes (see also table 3): lead, lead containing mechanism (concept B), eraser unit (concept A), body (concept B), lead pushing-out mechanism (concept A) and lead guiding mechanism (concept A). The second aggregation (between *HA* and the solution related to ‘meet safety requests’) generates a hybrid *HB* that includes: lead, lead containing mechanism (concept B), eraser unit (concept A), body (concept C), lead pushing-out mechanism (concept A or C) and lead guiding mechanism (concept C). The third aggregation requires innovation. In this respect, TRIZ method is here applied. From the complex set of conflicting problems between solution *HB* and solution related to ‘minimum costs’ only three have been extracted in this case study for exemplification: a) manufacturability versus convenience of use; b) durability of moving objects versus complexity of device; c) amount of substance versus complexity of device. According to TRIZ, the following inventive principles should be taken into account during the last aggregation step: 1) make an mobile/movable part immobile/immovable or vice versa; 2) place objects in advance in a way they can go immediately into action when required and they can do this from the most convenient position; 3) extract a

‘disturbing’ part or property from an object; 4) transition from a homogeneous structure to a heterogeneous structure; 5) ‘consolidate’ in space homogeneous objects; 6) divide an objects into elements that are able of changing their position relative to each other; 7) replace a symmetrical form with an asymmetrical forms or with several asymmetrical forms.

As most of the inventive principles reveal (especially principle 4), *HB* variant should be taken as reference instead of the local solution related to the objective-function ‘minimizing costs’. However, simplifications to *HB* should be done to meet the spirit of the objective-function ‘minimizing costs’. In this respect, modifications have been done to *HB* variant following the inventive principles above presented. The final result (hybrid *HC*) is shown in figure 12 (hand sketch of assemble for the overall solution) and in figure 13 (hand sketch of main sub-systems for the overall solution). Principle 1 is seen in making immovable the top of the pushing-out mechanism. Principle 2 is seen in the design of the lead guiding mechanism. Principle 3 is applied to extract the eraser unit from the system, as long as it has no big impact in the equation of product competitiveness. Also principle 3 is responsible for removing the metallic tip of the lead guiding mechanism. Principle 4 plays a major role in balancing the pencil’s concept to an ‘automatic’ one rather than to a classical wooden pencil. Principle 5 has a major contribution to the design of the lead containing mechanism in connection with the lead pushing-out mechanism and with the lead guiding mechanism, as well as to the design of the lead guiding mechanism. Principle 6 plays the key role in designing the new body of the pencil, in connection with the lead guiding mechanism. It is elaborated a design that makes the pencil to look like a pen – exactly what business objective *BR*<sub>3</sub> expresses. Actually, the pencil is design such as, anytime, the user can replace the lead container with a pen writing unit (ISO 12757-2) and to use the pencil as a pen. Principle 7 also induces the ideas promoted by principle 6. Materials used are plastics and metallic alloys.

‘[insert figure 12 about here – see figure 12 at the end of the body text]’

Figure 12. Overall solution (hand sketch of assemble).

‘[insert figure 13 about here – see figure 13 at the end of the body text]’

Figure 13. Overall solution (hand sketch of sub-systems).

Once the overall solution is defined, step 8 of the CMFD method is further applied to plan the mechanisms belonging to the overall solution. For this example, four planning matrices should be elaborated. Each of them is related to a given objective-function. The inputs into the matrices are the value characteristics and their ranks (see the outputs in figures 6 to 9). The outputs are the mechanisms of the overall solution and their calculated value weights. Because of space constrains, in this paper only the results of the planning process are introduced. The planning matrices are less relevant for the purpose of this case study (they are simple QFD-type matrices that look like those in figures 6 to 9). Further, relationships (7) and (8) are considered to establish the overall value weight of each mechanism. These results are comprised in table 4.

‘[insert table 4 about here – see table 4 at the end of the body text]’

Table 4. Mechanisms of the final solution and their local & overall value weights.

The results in table 4 show that the lead plays a key role in the equation of competitiveness (27.7%). Usually, for automatic pencils leads are standardized components, so people can use leads from various producers. However, the producer of this pencil can develop its own lead manufacturing unit if he wants to give a special attention to the quality of leads and to brand them afterwards. Besides lead, the key role in the equation of competitiveness is given by the body assemble (23.5%) and by the guiding mechanism (17.5%). Also the chuck mechanism is important to achieve a high quality product (12%). Because of this reason, the manufacturing quality of these



modules is very important for ensuring a commercial success. The planning process from step 8 is also important to give a perspective about the justified costs to produce each module. For example, if the cost objective is  $X$ , the cost objective to produce the body assemble should not be higher than  $X \cdot 0.235$ . Using this information, engineers can adjust their design if necessary, before doing further efforts in production planning.

Starting with step 9 of the CMFD method, product value characteristics are deployed into production. This means, once the design is well-defined, further success will be determined by the quality of the production processes. In this respect, product value characteristics should be linked ('transferred') both to part properties and production process properties. The final solution of the pencil comprises the following parts: 1) lead; 2) cover of the lead container (that also interfaces with the guiding mechanism); 3) lead container; 4) chuck; 5) chuck's ring; 6) chuck's spring; 7) lower body; 9) lower body's spring; 10) tip conducting tube; 11) top of the lead container; 12) hanger; 13) upper body; 14) upper body's spring; 15) metallic top of the upper body; 16) pushing-out button; 17) guiding element of the pushing-out button. Lead and springs are actually purchased by an external supplier. The other parts of the pencil are manufacture in-house. With respect to these parts, the production processes are: 1) moulding; 2) rolling; 3) cutting; 4) form turning; 5) facing; 6) forming; 7) polishing and 8) assembly.

From the analysis of part design, the following key part properties would be considered: 1) homogeneity of materials; 2) roughness of the surface; 3) accuracy of the parts' shape; 4) manufacturability properties of chosen raw materials. In terms of processes, the following key process properties should be taken into account: 1) process accuracy; 2) process controllability; 3) process simplicity (number of inter-correlated process' parameters for the critical manufacturing operations (e.g. correlation between speed, acceleration, move, temperature, time, pressure, etc.)). To keep the exercise still simple, not an exhaustive set of key properties have been considered here; only the most critical ones.

The key properties are concurrently planned against the value characteristics. Four planning matrices are worked out for this case study. Just for exemplification, the first matrix is presented in figure 14. The full results of this planning phase are shown in table 5. Relationships (9) and (10) have been used to determine the overall value weight of each key property. The accuracy of manufacturing operations and the accuracy of parts' shape seem to be critical properties for ensuring the final product quality.

[insert figure 14 about here – see figure 14 at the end of the body text]

Figure 14. Product and process key properties planning against quality value characteristics.

[insert table 5 about here – see table 5 at the end of the body text]

Table 5. Planning of product and process key properties against the overall set of value characteristics.

The step 11 of the CMFD method requires deploying part and process key properties into manufacturing operations. This step very much depends on the particular machine-tools, equipments and technologies the manufacturer has available. Also, the degree of difficulty depends very much on the technology and experience the manufacturer has available. For example, a manufacturing parameter that is considered of difficulty 2 by a certain manufacturer could be appreciated as being 4 by another manufacturer.

The key manufacturing parameters are extracted from the technological sheets of parts. An exhaustive list could contain a significant number of manufacturing parameters. Considering the limited space of the paper, the working principle of step 11 is illustrated on a restricted set of manufacturing parameters. Figure 15 gives the view on how step 11 of the CMFD method is elaborated. Only some of the parameters from the moulding and forming (stamping) operations are extracted here for exemplification. Also, in figure 15 only those parts that are manufactured in-house are introduced.

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[insert figure 15 about here – see figure 15 at the end of the body text]

Figure 15. Exemplification of planning the manufacturing operations.

Even if the exercise in figure 15 does not show the entire planning matrix and the final results, it is obvious that the pencil proposed in figure 12 should not raise difficulties in being manufactured, because today's technologies of manufacturing pencils are enough mature.

## 6 Recommendations for implementation

CMFD method is a tool that meets the latest industry needs in product design. For example, as the European Robotics Platform (EUROP) recently mentioned (May 2006) in its Strategic Research Agenda with time horizon 2020, one of the major challenges for future robotic products in all application domains will be the so-called 'design for dependability', that is {design for safety; design for liveness; design for timeliness; design for robustness; design for resilience; design for fault tolerance}. In the same spirit, the National Research Council from USA shows, in the report called 'Visionary Manufacturing Challenges for 2020', that reconfigurable equipments will be top technological priorities around year 2020. In this respect, 'design for reconfigurability' means {design for modularity; design for integrability; design for customization; design for convertibility; design for scalability; design for diagnosability}. More than this, countless studies highlight the future importance of 'design for tele-service' in industrial product design, meaning {design for reconfigurability; design for self-maintenance; design for reliability; design for self-learning; design for real-time process change detection; design for low cost redundant systems}. To these, 'design for product life-cycle' is the top challenge, that is {design for quality; design for conformity; design for manufacturing; design for assembly; design for testing; design for easy service and tele-service; design for easy use; design for easy maintenance and self-maintenance; design for reliability; design for easy replacement; design for environment; design for de-assembly; design for recycling; design for reuse}. It is obvious that in such circumstances, tools like CMFD will be crucial for a good product planning.

The complexity for all practical cases presented above is definitely very high. In this respect, people already realized that complex products of the future cannot be developed by a single company. From here, strong networks of companies, universities and research institutes have been established at international level. Such networks are organized in the so-called 'technological platforms' and comprise tens of organizations with complementary competences. Under such business models, the implementation of CMFD framework is fully achievable, considering both human and financial resources. The current developments of communication technologies and information technologies make possible to build distributed feature teams, as CMFD framework requires. They can use multiple facilities offered by Internet and Intranet-based tools for communication and work (e.g. specialized portals, VPN connection to various servers, messaging tools – see Yahoo messenger, Internet-based video and tele-conference tools – see Skype, repository applications for handling multiple-format documents – see CVS, on-line multi-level working tools – see Live Meeting from Microsoft, as well as many other ITC solutions like, for example, the Smart boards). Using the existent ITC solutions, the concurrent approach required by the CMFD framework is realizable. To this, the use of Web-based software for concurrent product planning is very useful, too. It might be a new opportunity the development of specific portals for Web-based concurrent product planning. However, some already existing software packages, like Qualica QFD<sup>TM</sup>, can support – with some improvements (i.e. using Qualica Script facilities) – the implementation of the CMFD framework in a digital environment.

In terms of the size of the planning matrices, as well as of the feature teams, there are no theoretical restrictions. However, from practical considerations, the planning matrices should not exceed in size the limit  $40 \times 40$  and the feature teams should not exceed the size of 6 people. People in the feature teams could be located in several centres. A team leader must be in charge for each

1  
2 feature team. In order to have a good management of all feature teams, Web-based project  
3 management tools have to be taken into account, too.

4  
5 **7 Conclusions**

6  
7 The CMFD method makes a step forward in supporting the so-called ‘design for excellence’  
8 concept (design for multiple objective-functions). Its algorithm is scientifically designed by means  
9 of the TRIZ method. The CMFD method brings the following contributions to existent practices of  
10 product planning: a) provides an elegant way to harmonize product planning with product design  
11 when multiple objective-functions are taken into account; b) provides a way to aggregate local  
12 solutions (developed by different teams, in different locations) into an overall solution; c) provides  
13 an effective way for deploying product planning to production planning and to asses the ‘quality’ of  
14 mechanism and part design through production characteristics; d) introduces a new view on the  
15 deployment process – from serial in one dimension to concurrent in three dimensions: concurrent in  
16 the sense that multiple functions or design perspectives could be taken into account and approached  
17 simultaneously (reflecting on this way the characteristics of complex systems); concurrent in the  
18 sense that various aspects of product or process planning do not necessarily follow a chain of  
19 deployments, as classical theory suggests (e.g. 4-Phase QFD Clausning model) – value  
20 characteristics are inputs for deployment in various phases of the CMFD method; concurrent in the  
21 sense that complementary issues from different areas can be used simultaneously to analyse a given  
22 problem – see step 10 and step 11 of the CMFD method; e) provides a reliable framework of  
23 cooperation between ‘distributed’ teams (networks of specialists) during the product development  
24 process – this meets the current business model approaches; f) demonstrates that product design and  
25 product planning are strongly interdependent at various stages of product development process and  
26 provides a way to ‘translate’ planning into design and vice versa; g) introduces a new vector to  
27 exploit innovation – the harmonization of different views about the same system using TRIZ or  
28 other inventive problem solving tools (see step 7, stage 4; by now, the use of TRIZ within QFD was  
29 mainly focused on the conflicts within the ‘roof’ of the House of Quality).

30  
31 CMFD method is thought for those companies that intend to manufacture world-class  
32 products for meeting the challenges of the future market environment. Besides other aspects,  
33 CMFD method shows that, as long as the external constraints increase in number and magnitude,  
34 like for example, the pressure to decrease the time-to-market and to increase product excellence  
35 (quality, performance, cost, etc.), the primary resources where a world-class company could mainly  
36 act to overpass these barriers are the internal processes. A world-class company has to implement  
37 concurrent approaches in product development such as to decrease the time-to-market while  
38 increase the degree of excellence induced into the product. In this respect, companies have to use  
39 proper planning and designing tools for transposing into practice the concurrent development  
40 process. It is obvious that, in such circumstances, the number of people involved in the design and  
41 development process should increase with the reduction of the cycle time and with the increase of  
42 product excellence. A balance in satisfying company’s stakeholders has to be achieved and the  
43 success is strongly dependent on how well both the managerial, organizational and technical aspects  
44 are solved.

45  
46 **Acknowledgements**

47  
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50  
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No.	Conflicting problems (see symbols in text)	Inventive vectors from TRIZ	Possible practical solutions
1	CP1, CP3, CP4	Segmentation (divide the system into independent parts)	QFD matrices for each objective-function; Customized QFD matrices; Each objective-function to be treated independently at each deployment phase; Customized deployment phases for each objective-function
2	CP4, CP7	Extraction (extract from the system only the disturbing or necessary parts or properties)	Relationship analysis within QFD is better to be done independently on each objective-function, in each deployment phase
3	CP3, CP7	Dynamicity (interchangeable system or mobile, automatic adjustment or alteration of parts for optimal functioning)	Analyse independent results and negotiate them concurrently to set up the final version and move to the next step; Use clear algorithms for negotiation; Share knowledge and tools between interdisciplinary teams; Share results (e.g. when define characteristics)
4	CP1, CP5	Mechanical vibration (put the system to vibrate, increase frequency of vibration)	Put the function-teams to communicate frequently, at least at the end of each deployment phase; Ask teams to “fight” for their solutions based on criteria (see common overall criteria, like business-related ones); Rank the objective-functions; Consider value characteristics instead of quality characteristics when plan
5	CP5, CP6	Change the colour (change transparency, use additives)	Use extra-tools to perform specific tasks that support planning; Use concurrent approaches when analyse results; Use the same rules for defining correlations and relationships
6	CP3, CP6	Rejecting and regenerating parts (restore the part of the system during operation when necessary)	From partial local solutions to partial overall solution and vice versa; Use iterations when generate the overall solution
7	CP1	Phase transition (use the effects generated over the transition phase)	Share useful results between the deployment lines of the objective-functions; Plan local variants
8	CP2	Inversion (turn the system upside down)	Concurrent approach at each phase; Minimize the set of inputs and outputs at each phase (focus on those having strong and very strong influence)
9	CP2	Copy (use simple copies instead of a single, complex system)	Approach local solutions and use them to define the overall solution
10	CP3	Partial or excessive action (try to achieve as much as possible if 100% is not possible)	If possible, keep the same algorithm for analysing relationships and correlations
11	CP4	Translation into a new dimension (multi-dimensions, multi-level joining, use the opposite side, too)	Simultaneous deployment of each objective-function; Link deployment lines after each deployment phase for analysis and adjustments
12	CP4	Composite structure (from homogeneous to composite)	Multi-disciplinary teams on each objective-function; Networks of teams if necessary; Mix of tools in a project team; Combine high risk-low risk approaches
13	CP5	Useful actions in advance (perform in advance total or partial useful actions)	Define in advance the technical characteristics
14	CP5	Inert environment (introduce a neutral additive)	Time-out during negotiation of solutions; Use TRIZ to solve conflicts
15	CP6	Mediation (use temporary an intermediary system to perform some tasks)	Integrate CMFD with other tools for design, analysis, evaluation, etc.
16	CP6	Replace the rigid system (use soft, flexible components)	Communication between teams; Transfer of results between teams; Flexible interfaces
17	CP7	Change properties (change flexibility, density, volume)	Define enough detailed steps to avoid loss of relevant information
18	CP7	Turn a harmful factor into a positive one	Use limited resources to explore new tools within the planning process; Define an algorithm that can be implemented into a software solution

Table 1. Inventive vectors of intervention and possible related practical solutions.

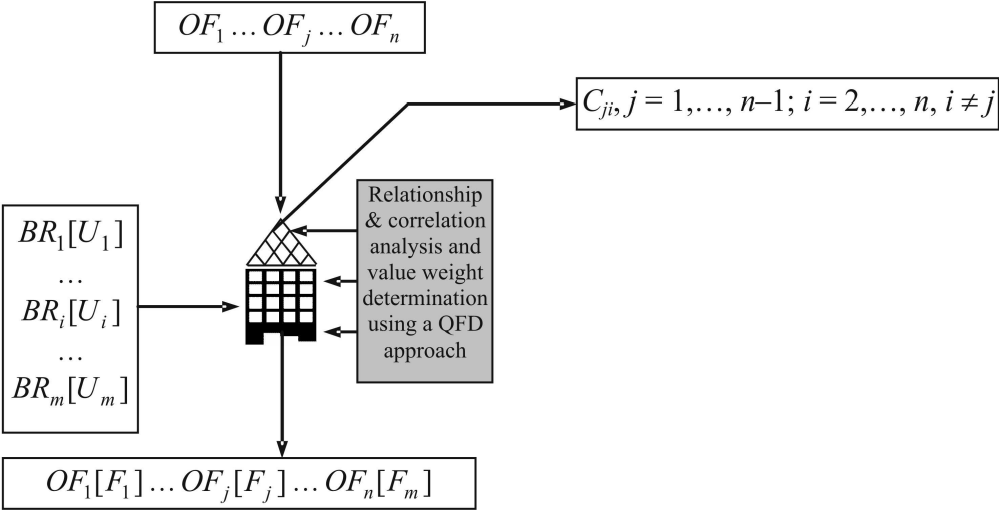


Figure 1. Analysis of the objective-functions against the business requirements

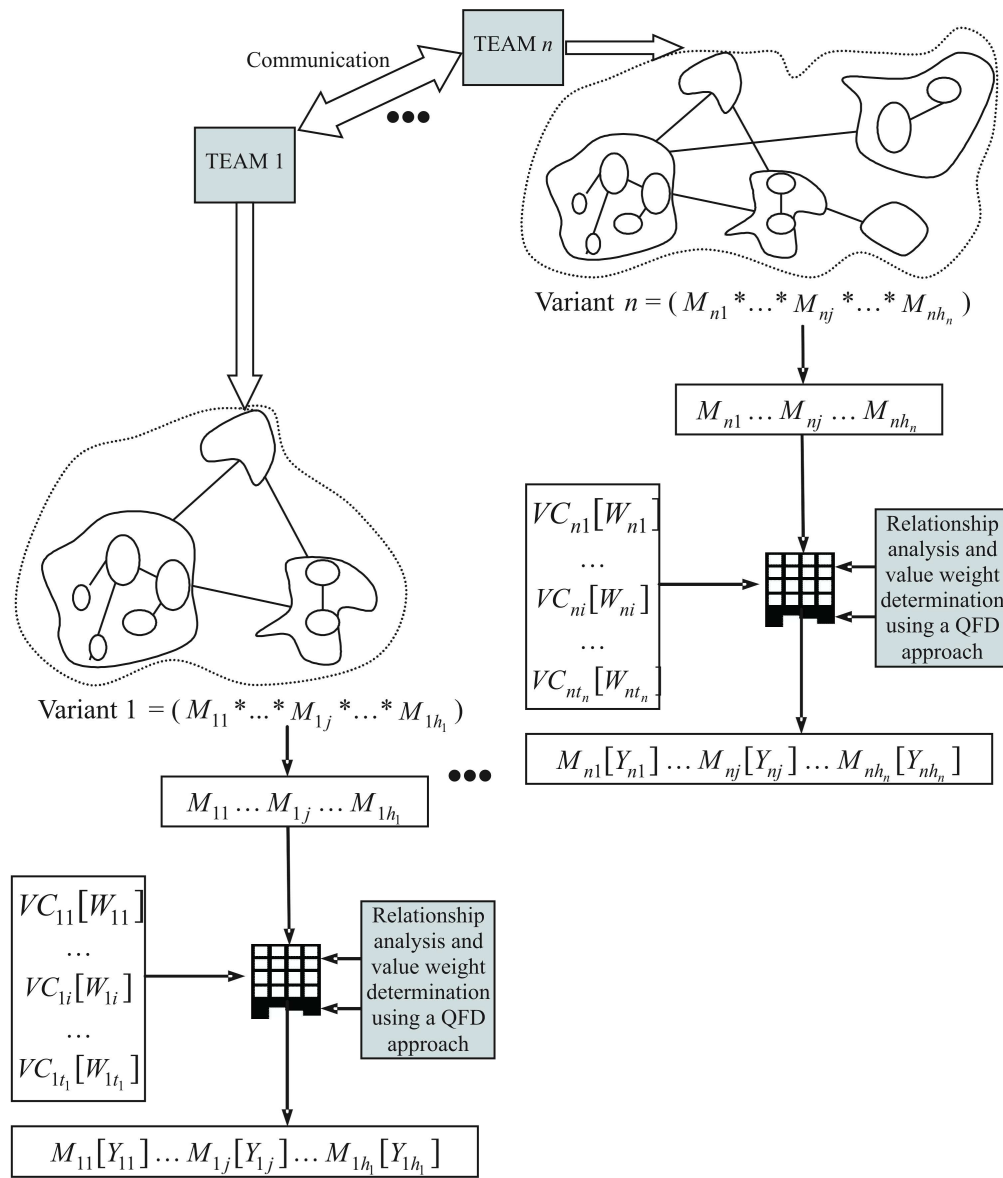


Figure 2. Deploy concurrently the local variants (designed at mechanism-level)

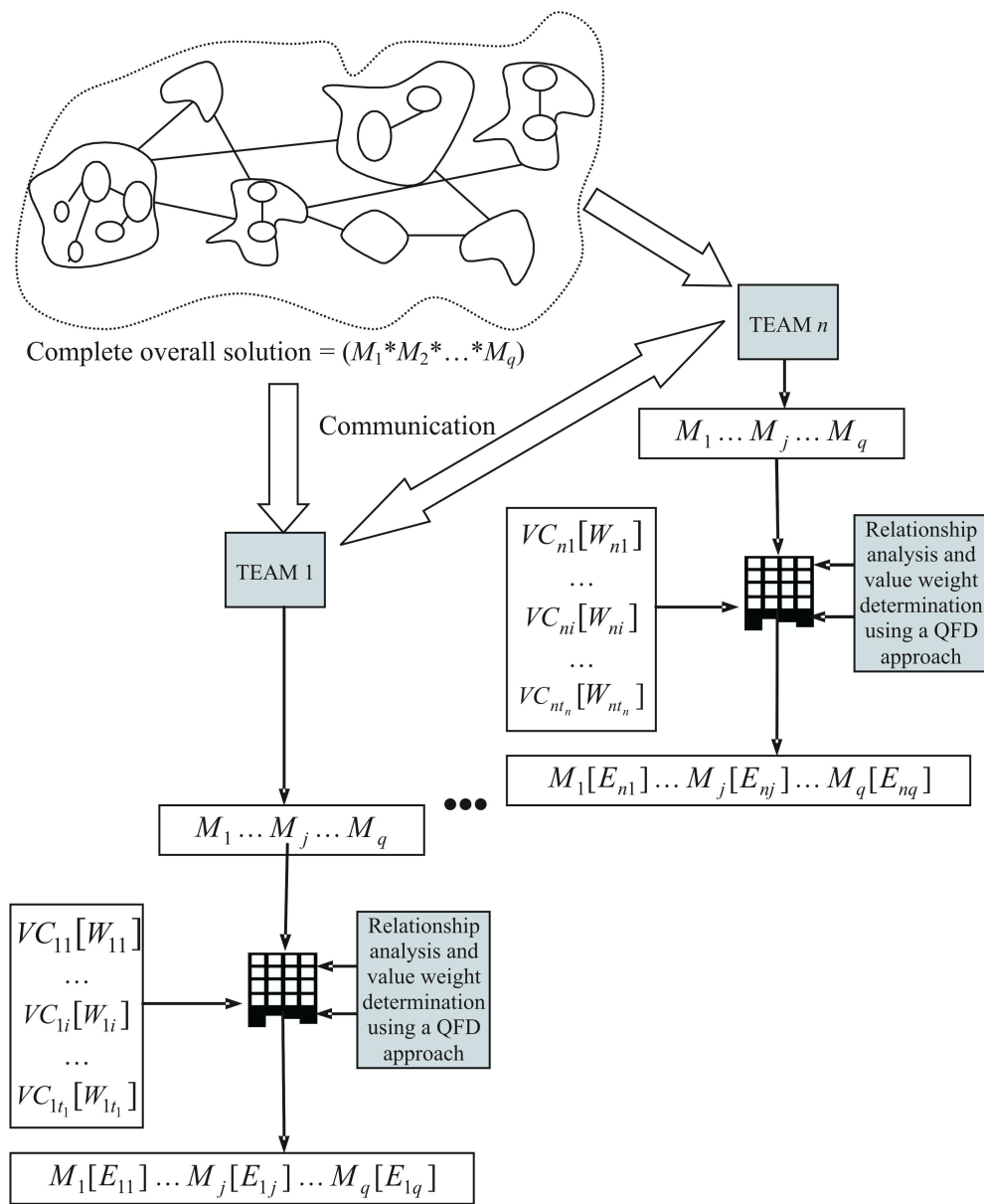


Figure 3. Analysis of the complete overall solution with respect to each objective-function

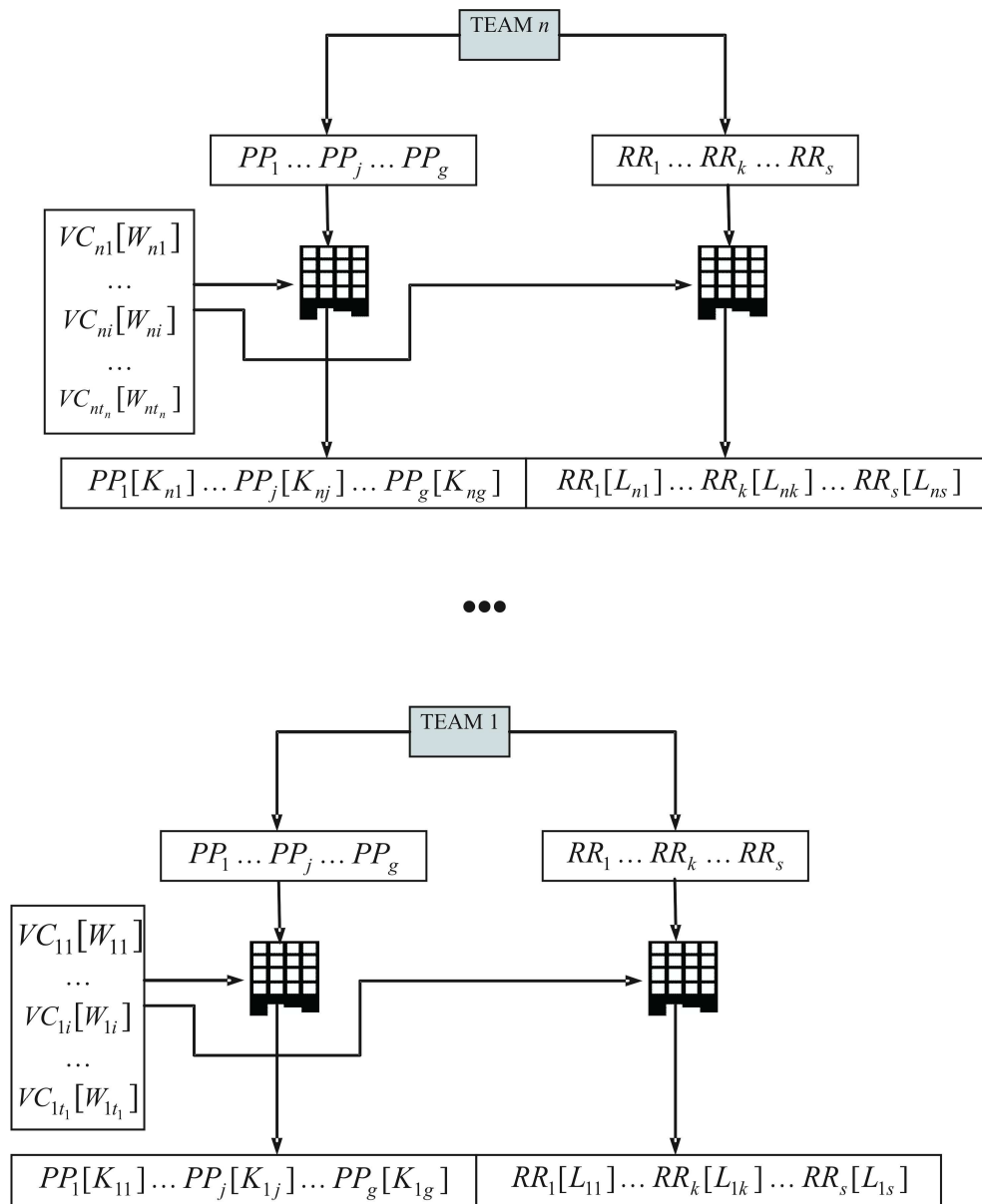


Figure 4. Planning concurrently parts and processes



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No.	Objective-function	Code	Requirement	Local rank [%]
1.1	High quality	$RC_{11}$	Ergonomics (easy to hold)	$R_{11} = 13\%$
1.2		$RC_{12}$	Aesthetics and personality	$R_{12} = 13\%$
1.3		$RC_{13}$	Point lasts for pencil tip	$R_{13} = 22\%$
1.4		$RC_{14}$	Easy to erase	$R_{14} = 13\%$
1.5		$RC_{15}$	To write with no effort	$R_{15} = 9\%$
1.6		$RC_{16}$	Pencil tip does not scratch	$R_{16} = 17\%$
1.7		$RC_{17}$	Pencil tip does not smear and / or roll	$R_{17} = 13\%$
2.1	High reliability	$RC_{21}$	Pencil tip does not break to usual forces during writing	$R_{21} = 35\%$
2.2		$RC_{22}$	Pencil length lasts	$R_{22} = 30\%$
2.3		$RC_{23}$	Pencil body resistant to bending forces (see behaviours)	$R_{23} = 20\%$
2.4		$RC_{24}$	Does not break when falling down on the floor	$R_{24} = 15\%$
3.1	Meet safety requests	$RC_{31}$	External surface not toxic (see various people behaviours)	$R_{31} = 50\%$
3.2		$RC_{32}$	Resistant to hand sweat	$R_{32} = 15\%$
3.3		$RC_{33}$	Avoid accidents when used by children	$R_{33} = 35\%$
4.1	Minimum costs	$RC_{41}$	Easy to manufacture	$R_{41} = 34\%$
4.2		$RC_{42}$	Few components	$R_{42} = 33\%$
4.3		$RC_{43}$	Cheap materials	$R_{43} = 33\%$

Table 2. Objective-function related requirements and their relative ranks.

Minimum costs						
Meet safety requests					--	
High reliability				++	--	
High quality			++	++	--	
Optimisation trends		↑	↑	↑	↓	
Legend: ⊙ strong relationship ○ medium relationship △ possible relationship ↑ maximization ↓ minimization ++ positive correlation -- negative correlation		Level of importance	High quality	High reliability	Meet safety requests	Minimum costs
$BR_1$ – to address both to pupils, students, specialists and usual people		60%	⊙	⊙	⊙	⊙
$BR_2$ – to address to various cultural trends and / or traditions		30%	⊙	○	○	○
$BR_3$ – to influence more people in using pencils in an age when pens and computers & printers are strong substitutes		10%	⊙	○	△	○
Value weight		31.5%	23.1%	22.4%	23.1%	

Figure 5. Planning matrix of objective-functions

Legend:  
⊙ strong relationship  
○ medium relationship  
△ possible relationship

Value characteristics		Angle when rolling	Length	Size of the cross section	Shape of external surface	Time between sharpening	Dust generated when write	Dust generated when erase	Colour	Written pages / pencil	Cycles to erase	Shape of the pencil tip	Level of importance
No	Requirements	1	2	3	4	5	6	7	8	9	10	11	
1	Ergonomics (easy to hold)		⊙	⊙	⊙								13%
2	Aesthetics and personality		○	○	⊙				⊙				13%
3	Point lasts for pencil tip	○				⊙	⊙			⊙		⊙	22%
4	Easy to erase							⊙			⊙		13%
5	To write with no effort	○				⊙				⊙			9%
6	Pencil tip does not scratch	⊙				○						⊙	17%
7	Pencil tip does not smear and / or roll	⊙				○	⊙			⊙		△	13%
Value weight		13.5%	5.8%	5.8%	8.7%	13.7%	11.7%	4.3%	4.3%	14.7%	4.3%	13.0%	

Figure 6. Planning matrix of value characteristics related to objective-function 'high quality'

Legend: ⊙ strong relationship ○ medium relationship △ possible relationship		Value characteristics				Level of importance
		Strength to impacts	Strength to pressure - graphite	Bending strength	Pencil length	
No	Requirements	1	2	3	4	
1	Pencil tip does not break to usual forces during writing		⊙	○		35%
2	Pencil length lasts		○		⊙	30%
3	Pencil body resistant to bending forces (see behaviours)			⊙	○	20%
4	Does not break when falling down on the floor	⊙			○	15%
Value weight		11.2%	33.8%	23.8%	31.3%	

Figure 7. Planning matrix of value characteristics related to objective-function 'high reliability'

Legend: ⊙ strong relationship ○ medium relationship △ possible relationship		Value characteristics				Level of importance
		Material property of the external layer	Shape of the cross section	Shape of the pencil tip	Texture of the external layer	
No	Requirements	1	2	3	4	
1	External surface not toxic (see various people behaviours)	⊙				50%
2	Resistant to hand sweat	⊙	△		⊙	15%
3	Avoid accidents when used by children		⊙	⊙	○	35%
Value weight		39.8%	22.4%	21.4%	16.3%	

Figure 8. Planning matrix of value characteristics related to objective-function 'meet safety requests'



Legend: ⊙ strong relationship ○ medium relationship △ possible relationship		Value characteristics	Number of components	Geometry of components	Type of materials	Level of importance
No	Requirements		1	2	3	
1	Easy to manufacture		○	⊙	⊙	34%
2	Few components		⊙			33%
3	Cheap materials				⊙	33%
Value weight			30.5%	23.4%	46.1%	

Figure 9. Planning matrix of value characteristics related to objective-function 'minimum costs'



Figure 10. Local solutions (hand sketches of assemblies): from left to right - quality, reliability, safety, costs  
270x179mm (96 x 96 DPI)

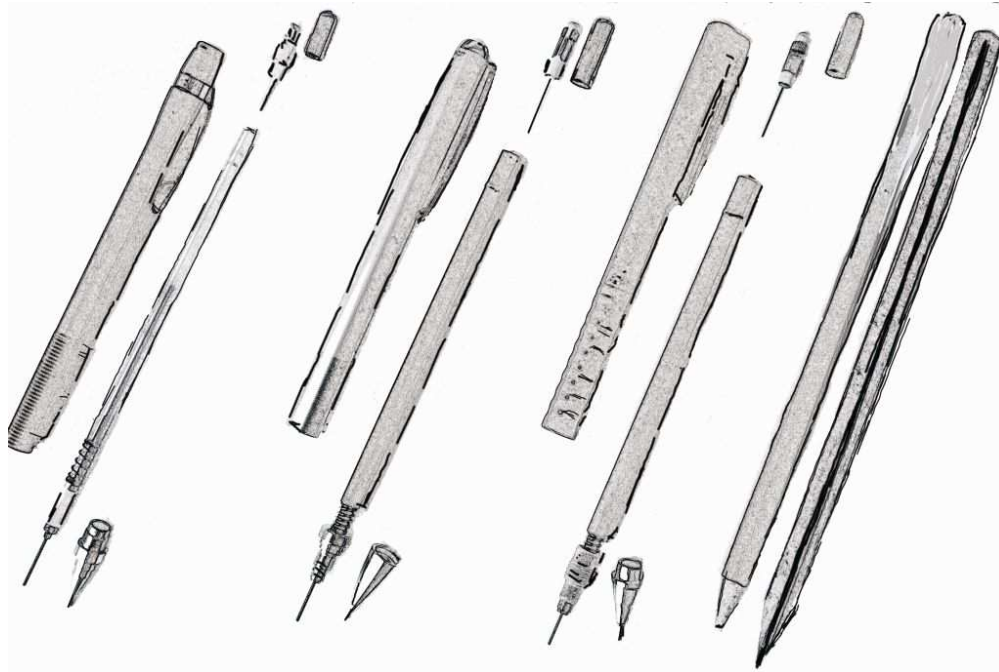


Figure 11. Local solutions (hand sketches of sub-systems): from left to right - quality, reliability, safety, costs  
270x182mm (96 x 96 DPI)

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No.	Objective-function	Mechanisms (sub-systems)	Calculated value weight [%]
1.1	Technical solution related to high quality	Lead	35.7%
1.2		Lead containing mechanism (concept A)	16.5%
1.3		Eraser unit (concept A)	4.8%
1.4		Body (concept A)	13.9%
1.5		Lead pushing-out mechanism (concept A)	10.5%
1.6		Lead guiding mechanism (concept A)	18.7%
2.1	Technical solution related to high reliability	Lead	32.2%
2.2		Lead containing mechanism (concept B)	16.6%
2.3		Eraser unit (concept B)	1.1%
2.4		Body (concept B)	28.0%
2.5		Lead pushing-out mechanism (concept B)	4.9%
2.6		Lead guiding mechanism (concept B)	17.2%
3.1	Technical solution related to safety requests	Lead	11.2%
3.2		Lead containing mechanism (concept C)	7.6%
3.3		Eraser unit (concept C)	4.6%
3.4		Body (concept C)	41.1%
3.5		Lead pushing-out mechanism (concept C)	10.8%
3.6		Lead guiding mechanism (concept C)	24.7%
4.1	Technical solution related to minimize costs	Graphite ('Lead')	29.4%
4.2		Binding 'mechanism'	22.3%
4.3		Body 'sub-assemble' 1	24.1%
4.4		Body 'sub-assemble' 2	24.1%

Table 3. Sub-systems for local solutions and their relative value weights.



Figure 12. Overall solution (hand sketch of assemble)  
185x270mm (96 x 96 DPI)





Figure 13. Overall solution (hand sketch of sub-systems)  
270x165mm (96 x 96 DPI)

No.	Mechanisms of the final solution	High quality		High reliability		Meet safety requests		Minimum costs		Final value weight [%]
		$FN_1$	$E_{1k}$ [%]	$FN_2$	$E_{2k}$ [%]	$FN_3$	$E_{3k}$ [%]	$FN_4$	$E_{4k}$ [%]	
1	Lead		$E_{11}=44.6$		$E_{21}=29.3$		$E_{31}=11.3$		$E_{41}=19.1$	$E_1=27.7$
2	Lead container		$E_{12}=6.0$		$E_{22}=15.1$		$E_{32}=7.7$		$E_{42}=11.1$	$E_2=9.7$
3	Chuck mechanism	0.315	$E_{13}=11.5$	0.231	$E_{23}=9.9$	0.224	$E_{33}=3.8$	0.231	$E_{43}=22.7$	$E_3=12.0$
4	Pushing-out mechanism		$E_{14}=8.1$		$E_{24}=4.5$		$E_{34}=10.9$		$E_{44}=15.7$	$E_4=9.6$
5	Body assemble		$E_{15}=14.9$		$E_{25}=25.5$		$E_{35}=41.4$		$E_{45}=15.7$	$E_5=23.5$
6	Guiding mechanism		$E_{16}=15.0$		$E_{26}=15.7$		$E_{36}=24.9$		$E_{46}=15.7$	$E_6=17.5$

Table 4. Mechanisms of the final solution and their local &amp; overall value weights.

Legend:  
⊙ strong relationship  
○ medium relationship  
△ possible relationship

Part and process key properties		Homogeneity of materials	Roughness of the surface	Accuracy of the parts' shape	Manufacturability properties of chosen raw materials	Process accuracy	Process controllability	Process simplicity	Level of importance
No	Value characteristics	1	2	3	4	5	6	7	
1	Angle when rolling		⊙	⊙		⊙	○		13.5%
2	Length					⊙	⊙	○	5.8%
3	Size of the cross section		⊙	⊙	⊙	⊙	○	○	5.8%
4	Shape of external surface	△	⊙	⊙	○	⊙	⊙	⊙	8.7%
5	Time between sharpening	⊙			⊙	⊙	○	⊙	13.7%
6	Dust generated when write	⊙		⊙	△				11.7%
7	Dust generated when erase	⊙			△				4.3%
8	Colour		○			○	⊙	○	4.3%
9	Written pages / pencil	○			○				14.7%
10	Cycles to erase	○			○				4.3%
11	Shape of the pencil tip			⊙		⊙		⊙	13.0%
Value weight		13.1%	10.4%	18.7%	10.8%	22.0%	10.6%	14.4%	

Figure 14. Product and process key properties planning against quality value characteristics

No.	Part and process key properties	High quality		High reliability		Meet safety requests		Minimum costs		Final value weight [%]
		$FN_1$	$K, L [\%]$	$FN_2$	$K, L [\%]$	$FN_3$	$K, L [\%]$	$FN_4$	$K, L [\%]$	
1	Homogeneity of materials		$K_{11}=13.1$		$K_{21}=18.0$		$K_{31}=9.7$		$K_{41}=10.8$	$K_1=12.9$
2	Roughness of the surface		$K_{12}=10.4$		$K_{22}=4.2$		$K_{32}=13.4$		$K_{42}=17.0$	$K_2=11.2$
3	Accuracy of the parts' shape		$K_{13}=18.7$		$K_{23}=16.6$		$K_{33}=10.2$		$K_{43}=18.6$	$K_3=16.3$
4	Manufacturability properties of mat.	0.315	$K_{14}=10.8$	0.231	$K_{24}=6.0$	0.224	$K_{34}=27.8$	0.231	$K_{44}=18.6$	$K_4=15.3$
5	Process accuracy		$L_{11}=22.0$		$L_{21}=36.6$		$L_{31}=13.1$		$L_{41}=17.0$	$L_1=22.2$
6	Process controllability		$L_{12}=10.6$		$L_{22}=6.0$		$L_{32}=6.6$		$L_{42}=1.8$	$L_2=6.6$
7	Process simplicity		$L_{13}=14.4$		$L_{23}=12.7$		$L_{33}=19.1$		$L_{43}=16.2$	$L_3=15.5$

Table 5. Planning of product and process key properties against the overall set of value characteristics.

Legend: ⊙ strong relationship (9) ○ medium relationship (3) △ possible relationship (1)		Moulding					Forming (stamping)					Level of importance				
		Pressing time	Working pressure	Cooling time	Temperature	Die wear	...	Active drive	Active speed	Air jet pressure	Form wear				Came rotation in null	...
Part and process key properties		Main manufacturing operations / key parameters														
1	Homogeneity of materials	⊙	⊙	⊙	⊙	...	...	⊙	⊙		⊙	○	...	...	...	$K_1=12.9$
2	Roughness of the surface	○	⊙	⊙	⊙	⊙	...	⊙	⊙		⊙	○	...	...	...	$K_2=11.2$
3	Accuracy of the parts' shape	○	⊙	⊙	⊙	⊙	...	⊙			⊙	⊙	...	...	...	$K_3=16.3$
4	Manufacturability prop. of mat.	⊙	○	⊙	○	○	...	...	⊙		○		...	...	...	$K_4=15.3$
5	Process accuracy	⊙	⊙	⊙	⊙		...	...	⊙	⊙		⊙	...	...	...	$L_1=22.2$
6	Process controllability					⊙	...	...			⊙	△	...	...	...	$L_2=6.6$
7	Process simplicity	⊙	⊙	⊙	⊙		...	⊙	⊙	⊙		⊙	...	...	...	$L_3=15.5$
Value weight in absolute figures ( $Z_i$ )		672.5	744.2	832.4	744.2	352.8	...	584.3	573.3	137.8	352.8	523.7	...	...	...	
Target value of the parameter		To be specified	To be specified	To be specified	To be specified	To be specified	To be specified	To be specified	To be specified	To be specified	To be specified	To be specified	To be specified	To be specified	To be specified	To be specified
Part manufactured in-house		$D_{rt}$													$Q_r$	
1	Cover of the lead container	1	2	2	2	2	...						...	...	...	6019.7 + ...
2	Lead container	1	2	2	2	4	...						...	...	...	6725.3 + ...
3	Chuck						...						...	...	...	...
4	Chuck's ring						...						...	...	...	...
5	Lower body						...						...	...	...	...
6	Tip conducting tube						...	2	2	1	2	2	...	...	...	4206.0 + ...
7	Top of the lead container	1	2	2	2	2	...						...	...	...	6019.7 + ...
8	Hanger						...	1	1	1	2		...	...	...	2001.0 + ...
9	Upper body						...						...	...	...	...
10	Metallic top of the upper body						...	1	2	1	2	2	...	...	...	3621.7 + ...
11	Pushing-out button	1	2	2	2	2	...						...	...	...	6019.7 + ...
12	Guiding element	1	2	2	2	4	...						...	...	...	6725.3 + ...
															$Q_{41338.4} + ...$	

Figure 15. Exemplification of planning the manufacturing operations