OPTIMIZED DESIGN OF CONCRETE STRUCTURES WITH REGARD TO ENVIRONMENTAL ASPECTS

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Summary

This contribution describes a formulation of the optimized design of structures using the probability based method. The Monte Carlo simulation method, modified by the Latin Hypercube Sampling (LHS) method, was used for the calculation of the reliability of a designed structure. To find the best possible design for a structure an optimization procedure (method) was used. Economical and ecological aspects (acquisition costs, CO_2 and SO_2 emissions, photochemical ozone creation potential and embodied energy) associated with concrete member production, with utilization stage of and end of life cycle stage were taken into account in the objective function.

A design example – prestressed spun concrete pole made from reinforced concrete – is presented. The results are compared with optimized design, where reliability conditions were expressed by commonly used partial factor method.

Keywords: optimization, probability based design, environmental aspects, reinforced concrete

1 Introduction

The building industry is one of the largest consumers of material and energy resources and ranks among the largest producers of waste and harmful emissions. It is therefore useful to design a structure not from reliability and cost aspects, but so that its environmental impact is minimal. To find the best possible design for a structure or member without a negative effect on the reliability system as a whole it is necessary to use a suitable optimization method. It isn't really so useful to simply optimize the initial cost. It is far more advantageous to minimize the total cost, i.e. the cost over the life cycle of a structure, and to maximize the stiffness of the designed structure at prescribed cross sections.

A significant amount of the existing optimized methods are specialized in the area of structural design that considers all parameters as being deterministic (DBSO – Deterministic Based Structure Optimization). The general deficiency of DBSO is the omission of uncertainties while determining loads, material characteristics, responses and the stability of the structure. Elimination of that deficiency enables the combination of design methods based on comprehensive probabilistic approaches and optimized methods. This type of assessment is called Reliability Based Structure Optimization (RBSO).

The crucial conceptual problem is, however, the question of how to take stochastic variability into account, which especially concerns the properties of materials and general loading, and includes environmental, technical and technological aspects.

2 RBSO problem formulation

The task is defined as follows:

- the target function reaches the extreme

$$\{f(\{x\})\} = \text{ extreme,} \tag{1a}$$

while keeping the restrictive conditions

- from the reliability requirements of the designed structure expressed in probabilities

$$P_{fj}(\{x\}) \le P_{fj}^{0} \qquad j = 1,\dots,np \tag{1b}$$

- and from other conditions with the included further terms containing probabilities. These conditions can be expressed in the form of the equalities

$$\{h(\{x\})\} = \{0_1\} \tag{1c}$$

and the inequalities

$$\{g(\{x\})\} \le \{0_2\}, \tag{1d}$$

where $\{x\}=\{x_{s1},\dots,x_{snt}\}$T are the design variables, $\{f(\{x\})\}=\{f_1(\{x\}),\dots,f_t(\{x\})\}^T$ is the vector of the target functions, $f_i(\{x\})$ is the i-th target function, $\{h(\{x\})\}$ is the vector of the restrictive conditions in the form of equations, $\{g(\{x\})\}$ is the vector of the restrictive conditions in the form of inequalities, $P_{fj}(\{x\})$ is the probability of the structure's failure (the j-th condition of the reliability relating to some mode of failure or to applicability in a given locality), P_{0fj} is the permitted probability of the failure determined for the j-th conditions of the reliability, and $\{0_1\}$ and $\{0_2\}$ are zero vectors of the relevant type.

3 Assessment of the life cycle of an engineering construction

The methodology of life cycle assessment is defined in standards ISO 14040-14049. This methodology includes the following stages for a particular structure: the construction process, utilisation and the end of its life cycle. The following facts should be included in the individual stages:

- The construction process stage: This includes all operations connected with both the design and the construction. These are especially:
  - the exploitation of raw materials and other materials that will be incorporated into a structure or those used up during its production (exploitation of primary raw materials, modification of secondary materials),
  - manufacturing techniques used in material and member production,
  - techniques used in the construction process.

  All matters connected with transport, manipulation and storage should also be included in this stage.
- The utilisation and operation stage: This includes all activities connected with the operation of a structure, i.e.

  - maintenance (extent, frequency and technical procedures used),
  - repairs (extent, frequency and technical procedures used).

  All matters connected with the production, transport, manipulation and storing of the materials needed for maintenance and repairs or of the materials removed from the construction will be included in this stage.
- The end-of-life cycle stage includes:
  - the amount of rubble and/or demountable parts of the structure,
  - the influence of possible techniques used in the demolition/dismantling of the structure,
  - all matters connected with the transport, manipulation and storing of materials.

3.1 Target function

The optimisation problem of the concrete structure may be, e.g. according to [1], defined by the target function

$$\{f(\{x\})\} = f(\min E_{tot}, \min C_{tot}, \max S_{tot}), \quad (2)$$

where E_{tot} is the gross environmental impact, C_{tot} is the gross cost and S_{tot} is the gross socio-cultural quality. In a case when the Life Cycle Assessment of a structure is taken into account, it is possible to express

$$E_{tot} = E_{constr} + E_{oper} + E_{dem}, \quad (3)$$

$$C_{tot} = C_{constr} + C_{oper} + C_{dem}, \quad (4)$$

where E_{constr}, E_{oper}, E_{dem} are the environmental impacts for the construction, operation and demolition phases respectively; C_{constr}, C_{oper}, C_{dem} are the costs for the construction, operation and demolition phases respectively.

The determination of the total cost according to equation (4) is easy whereas the calculation of the gross environmental impact according to equation (3) is not. Commonly, we have to take into account the following aspects: consumption of primary raw materials, water consumption, global warming potential (GWP), acidification potential (AP), photochemical ozone creation potential (POCP), primary energy consumption, the amount of recyclable (reusable) materials and/or members (at the end of the lifetime of the analysed structure), and the amount of unrecyclable/unreusable materials/members (amount of waste).

It is possible to express the GWP via equivalent global warming potential GWP_{equiv}, which depends on equivalent CO_2 emissions (calculated for greenhouse gases CO_2, CO, NO_x, CH_6 and N_2O). The AP can be expressed as equivalent acidification potential AP_{equiv}, that depends on equivalent SO_2 emissions (calculated for chemical substances SO_2, NO_x, NH_3, HCl and H_2S). The POCP can be qualified as equivalent photochemical ozone creation potential $POCP_{equiv}$, which is depending on the equivalent emission of ethylene ($C_2H_{4,eqv}$) obtained from chemical substances C_2H_4, C_2H_6, CH_4, C_7H_8, acetate and aldehyde.

The consumption of primary raw materials and water, the equivalents for global warming potential GWP, acidification potential AP and photochemical ozone creation potential POCP, and the primary energy associated with the production of concrete are shown in Table 1. For some types of transport, the equivalents for global warming potential GWP, acidification potential AP and photochemical ozone creation potential POCP are shown in Table 2.

Tab. 1 *GWP_{equiv}, AP_{equiv}, $POCP_{equiv}$ and primary energy calculations for some components of concrete, see [2]*

	Gravel	Crushed gravel	Cement	High-range water reducer	Water	Production
Primary raw materials [kg/t]	1000.2	1024	2741	91.1	0	0
Water consumption [m^3/t]	0.0919	0.1232	2.0471	7.4	1	0.2092
GWP_{equiv} [kg/t]	2.53	2.41	778.9	2731.9	0.331	64.31
AP_{equiv} [g/t]	8.14	9.73	2424.8	19706.5	2.365	112.44
$POCP_{\mathrm{equiv}}$ [g/t]	0.09	0.12	82.6	1040.8	0.122	4.16
Primary energy [MJ/t]	38	35.85	4646.4	28857	5	1014.48

Tab. 2 *GWP_{equiv}, AP_{equiv}, $POCP_{equiv}$ and primary energy calculations for some types of transport, see [2]*

Transport	Long distance freight	Local freight	Railway freight
GWP_{equiv} [kg/t/km]	0.1011	0.2372	0.0764
AP_{equiv} [g/t/km]	0.7139	2.1091	0.1433
$POCP_{\mathrm{equiv}}$ [g/t/km]	0.0350	0.2095	0.0115
Primary energy [MJ/t/km]	1.3942	3.2039	0.9644

4 Solved structure – a spun concrete pole

The reinforcement of the pole is fabricated from prestressed indented 6 mm diameter Y1570C wires (øPN) which are supplemented by 10 mm diameter B500B passive reinforcement (øR). The prestressing wires are situated along the entire pole and are bond-anchored both at the top and bottom of the pole. Passive (non prestressed) reinforcement is designed in various lengths in order to contribute to the bearing capacity of the pole. The pole has an annular cross--section. The geometry of the pole is shown in **Fig. 1**.

The stress acting on the pole is given by the top horizontal force. The characteristic value of this force is V = 10 kN. It includes the tensions of cable lines and also climatic effects (such as wind and icing on overhead lines).

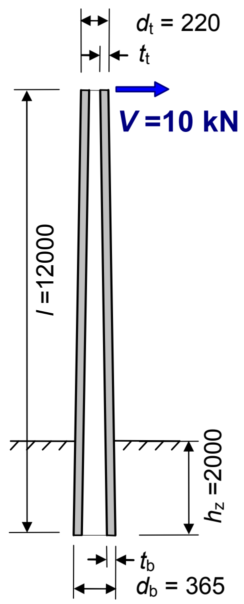

Fig. 1 *Geometry of the pole*

4.1 Objective function

The target function criteria involve economic, ecological and structural aspects (according to equation (2)). The gross socio-cultural quality S_{tot} was neglected. The lifetime assessment of the designed pole was formulated as follows:

- The construction process stage. It includes all operations described above. The resulting values are shown in Table 3; they were calculated according to the values given in Tables 1 and 2 for individual concrete components and reinforcement (amounts, distances and types of transportation are presented in **Fig. 2**). The average distance of pole transportation from the manufacturing facility to the destination is assumed to be 300 km; transport cost 40 €/t.

- Utilisation and operation phase – we do not consider the structure's lifetime, maintenance or repair because it is not common or necessary for this type of structure.
- The end-of-life cycle phase – we assume the dismantling or demolition of the structure. Transportation distance (about 100 km) and the type of transport were included in the calculated values. The unit costs and environmental impacts of the end of the structure´s life cycle are shown in Table 4.

Tab. 3 *GWP_{equiv}, AP_{equiv}, $POCP_{equiv}$ and primary energy calculations for some concrete components*

	Concrete		**Prestressed wire**		**Reinforcement**	
	Transport per m^3	Supply per m^3	Transport per t	Supply per t	Transport per t	Supply per t
Primary raw materials [kg]	-	2747.1	-	1881.2	-	1823.2
Water consumption [m^3]	-	1.30	-	2.92	-	3.09
GWP_{equiv} [kg]	13.49	348.8	52.88	2776.7	31.44	2505.4
AP_{equiv} [g]	74.91	1029.7	92.54	16325.0	55.02	15519.1
$POCP_{\text{equiv}}$ [g]	4.14	36.1	6.61	648.8	3.93	620.3
Primary energy [MJ]	179.88	2786.5	654.39	31895.2	389.07	27311.2
Cost in Euros	-	95.40	-	1200.00	-	948.00

Tab. 4 *Unit costs and environmental impacts of the end-of-life cycle phase*

	Primary Energy [MJ/t]	***GWP*equin** [kg/t]	***AP*equiv** [g/t]	***POCP*equiv** [g/t]	**Unit cost** [€/t]
End of life cycle	258.73	18.74	151.97	4.05	16.24

The objective function includes the costs and the environmental impact executed for the whole life time period of one pole. The optimization task is a multicriterial one and all the above mentioned aspects should be minimized. The method of weighted sums should be applied; the problem then becomes monocriterial and a suitable optimization algorithm can be selected. However, the terms of the objective function have different units and thus cannot be directly summed; for that reason they must first be normalized by the chosen reference values.

$$f(x) = +\alpha_{\text{GWP}} \frac{GWP_{\text{tot,equiv}}(\{x\})}{{}^{0}GWP_{\text{tot,equiv}}} + \alpha_{\text{AP}} \frac{AP_{\text{tot,equiv}}(\{x\})}{{}^{0}AP_{\text{tot,equiv}}} + \\ + \alpha_{\text{POCP}} \frac{POCP_{\text{tot,equiv}}(\{x\})}{{}^{0}POCP_{\text{tot,equiv}}} + \alpha_{\text{E}} \frac{E_{\text{tot}}(\{x\})}{{}^{0}E_{\text{tot}}} + \alpha_{\text{C}} \frac{C_{\text{tot}}(\{x\})}{{}^{0}C_{\text{tot}}} \tag{5}$$

where the used symbols have the following meanings: $C_{\text{tot}}(\{x\})$ is the total acquisition costs; $GWP_{\text{tot,equiv}}(\{x\})$ is the total equivalent global warming potential; $AP_{\text{tot,equiv}}(\{x\})$ is the total acidification potential; $POCP_{\text{tot,equiv}}(\{x\})$ is the total photochemical ozone creation potential; $E_{\text{tot}}(\{x\})$ is the total energy consumption; and α_{C} (or α_{GWP}, α_{AP}, α_{POCP}, or α_{E}) are weights in the objective function. ${}^{0}C_{\text{tot}}$, ${}^{0}GWP_{\text{tot,equiv}}$, ${}^{0}AP_{\text{tot,equiv}}$, ${}^{0}POCP_{\text{tot,equiv}}$, ${}^{0}\text{E}_{\text{tot}}$ are reference values for corresponding quantities calculated for the reference pole defined by the problem designer.

The following aspects were not included in the target function: consumption of primary raw materials, water consumption, the amount of recyclable (reusable) materials and the amount of unrecyclable/unreusable materials/members (amount of waste).

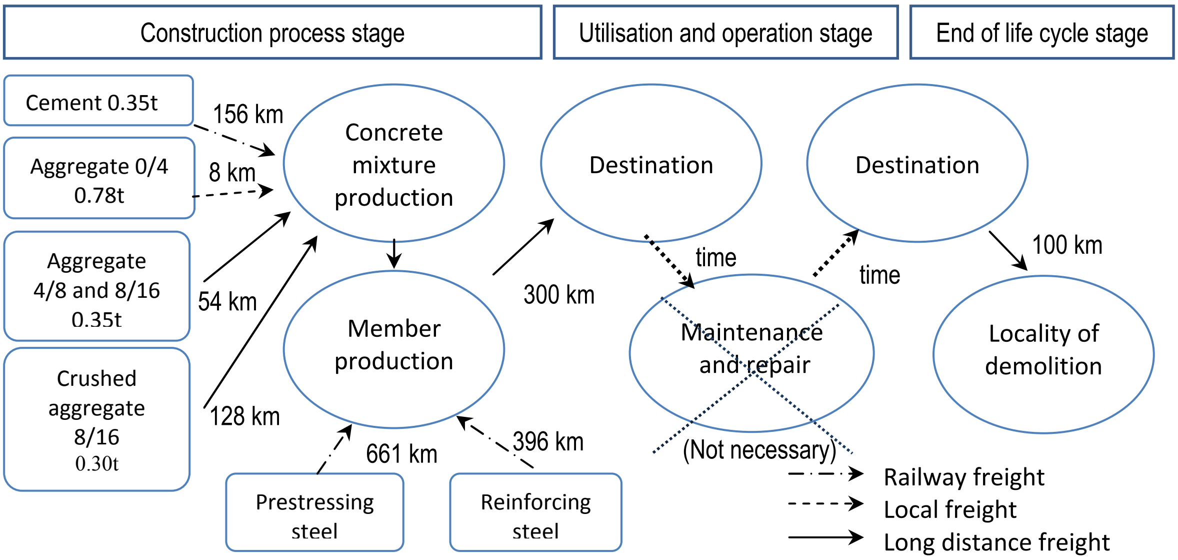

Fig. 2 *Life time cycle and individual concrete components, distances and types of transportation*

4.2 Restrictive conditions

Restrictive conditions are formed by the principles of standards EN 1990:2002 and ISO 2394:1998 which also enables the application of probability based methods, e.g. a probability based method (PBM) for the design and evaluation of structures. The resulting design has to meet the following reliability conditions:

- ultimate limit state (ULS): the pole is loaded by a normal force load (caused by prestressing) and bending moment (caused by the top horizontal force, V) in predefined discrete cross-sections along the pole length,
- serviceability limit state (SLS): the width of the crack for 1.0V load, crack origin at 0.5V load and deformation control should be checked.

The design was based on the assumption that the geometry of the pole is unchangeable (it is determined by the mould in which it is produced); only the thickness of the concrete, the number of prestressed strands and the passive reinforcement (number of bars, length of bars) were allowed to be changed. Maximum amount of prestressing wires was given due to limitation of distance between wires on head of pole (32 pcs), only an even number of wires is possible. Minimum thickness of cross-section wall of pole head (t_t) was 60 mm and 70 mm of foot of pole (t_b).

4.3 Method of solution

Analytical representation of the failure function is only possible in simple cases, and thus its application is limited. The failure function Z generally depends on the number of random quantities, whose distributions do not always correspond to the normal distribution. The relations for determining the effect of loading E and resistance function R

are often complicated and non-linear; therefore, numerical methods (simulation, semi analytical) are used for failure probability calculation.

Design and assessment were carried out with software based on the algorithms determined and mentioned in [3]. This software was set up primarily for use in the partial factor method but then was modified for application in fully probabilistic design. The Monte Carlo simulation method was used to calculate the reliability, modified by the Latin Hypercube Sampling method (LHS). Problems in optimum reliable design in civil engineering can be modelled by stochastic programming, see [3] and [4].

4.4 Input variables and characteristics

The statistical distributions of material characteristics and some geometric characteristics were provided by the producer of the poles, Sloupárna Majdaléna, while the uncertainties of the resistance model R and the calculation of the effect of loading E were taken from the recommendations of the JCSS Probability model code.

4.5 Results

The optimization of reinforcement was performed for objective function (5), in which five weighting coefficient alternatives were considered. In each alternative one of the considered weighting coefficients is equal to 1 and the others are equal to zero. The objective function is reduced on one of the summands expressing so that it expresses only one component of the monitored environmental impact. This is done in an effort to determine trends in emission amounts, energy consumption and prices.

Three types of poles were checked. They differed in the concrete thickness of their cross-sections (**Fig. 1**): Type 1 (t_t = 60 mm; t_b = 70 mm), Type 2 (t_t = 65 mm; t_b = 85 mm) and Type 3 (t_t = 70 mm; t_b = 100 mm).

4.5.1 Probability based method (PBM)

The reliability index was considered for the reliability class RC2 β_0 = 3.8 for ULS and β_0 = 1.5 for SLS. The proposed concrete reinforcement for each type of column (depending on the number of prestressing wires) was always divided into three groups. The groups varied in the length of the reinforcement used and its location along the length of the pole. The Type 1 pole – 22øPN (i.e. the pole with 22 pieces of prestressing wire) was considered to be a reference pole when evaluating the objective function.

The optimum design from the point of view of the minimization of:

- emissions is pole Type 1 – prestressed reinforcement 26øPN + non-prestressed reinforcement 17øR: $f(x)_{GWP}$ = 0.997; $f(x)_{AP}$ = $f(x)_{POCP}$ = 0.993,
- energy consumption is pole Type 1 – 24øPN + 18øR: $f(x)_E$ = 0.999,
- cost is pole Type 1 – 22øPN + 19øR: $f(x)_C$ = 1.000, i.e. the reference pole.

Poles with greater cross-section thickness (a larger volume of concrete) achieved higher objective function values (**Fig. 3**). Pole Type 2 and Type 3 with 22øPN did not fulfil the SLS reliability condition – crack origin at 0.5V load. Even the addition of more bars failed to achieve compliance with this condition, as the prestressing force is too small (insufficient) due to the larger area of concrete cross section compared to the Type 1 pole.

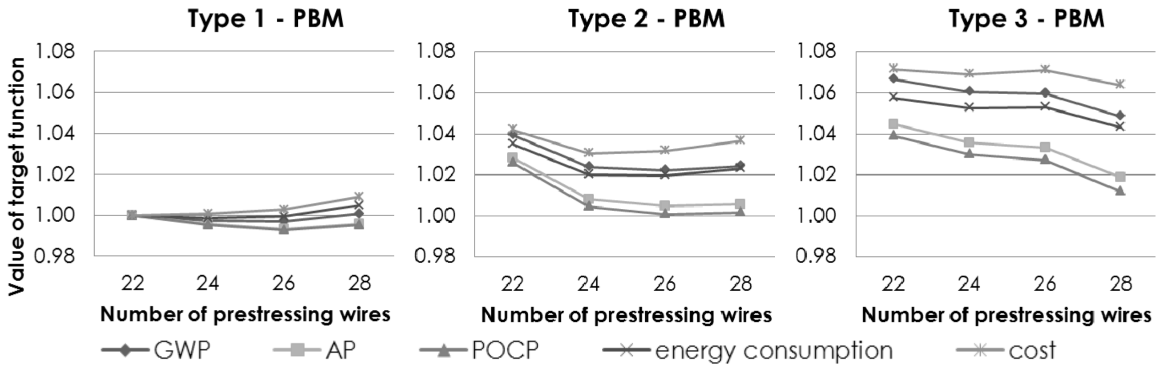

Fig. 3 Dependence of target function on type of pole and number of prestressing wires (PBM)

4.5.2 Partial factor method (PFM)

The proposed concrete reinforcement was divided into three groups for this method too. In terms of minimizing emissions, energy consumption and cost, the optimum pole is Type 1 – 22ø PN + 24øR, i.e. the reference pole.

Poles with greater cross-section thickness (a larger volume of concrete) achieved higher objective function values (**Fig. 4**).

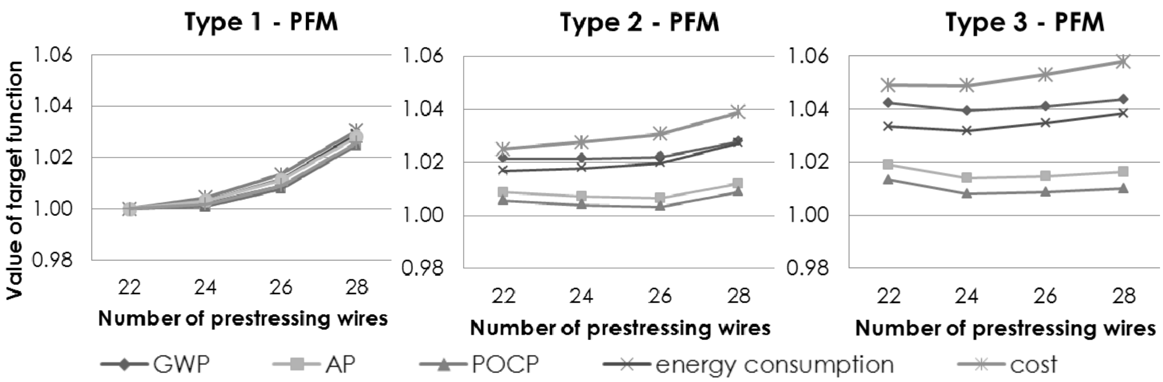

Fig. 4 Dependence of target function on type of pole and number of prestressing wires (PFM)

4.5.3 Comparison of both of the methods used

The results for poles designed using the PBM (optimum designs from the point of view of monitored component minimization) were compared with the proposed pole designed via the commonly used PFM. In the graph below (**Fig. 5**) it is clear that the design using PBM is efficient in all of the monitored aspects. The smallest saving is in cost (8.7 %), while the greatest saving (12.0 %) is for equivalent photochemical ozone creation potential.

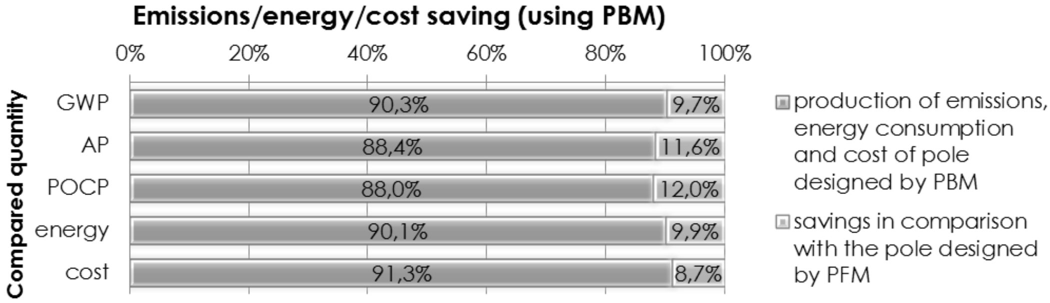

Fig. 5 *Comparison of savings in terms of environmental aspects, energy and cost when the PBM is used*

5 Conclusion

Probability based design better reflects the true characteristics of materials and geometry than the partial factor method. The mass production of members (poles) allows long-term monitoring and assessment of the fabricated product. The result is that the quality of products (product characteristics) can be taken into account during the design process.

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