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SOS – SUBJECTIVE OBJECTIVE SYSTEM FOR GENERATING OPTIMAL PRODUCT CONCEPTS

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Abstract

Concept design is the most critical step in product development. Support for concept generation is mainly intuitive. In this paper, we present a method – SOS (subjective objective system) – that is simple yet powerful, for generating optimal concepts in diverse disciplines. The method rests on four mathematical metaphors: it is composed of an objective and subjective components, it allows varying degrees of precision in modeling, it works by decomposing a complex problem into smaller sub-problems, and it uses highly simplified evaluations. SOS also reminds aspects of QFD but is quite different from it. It not only structures the decision process but also outputs the optimal concept given the customer objectives, the company context, and the available constraints. This solution is obtained by linear programming that allows the method to handle very large problems and solve them in negligible time. SOS has been evolved and refined over years of practical experience and research. The present version has been used in numerous successful real projects. We illustrate the use of the method in a realistic project.

Keywords: conceptual design, practice, linear programming, case study methodology, QFD, product configuration

1 Introduction

The concept of a product, i.e., its abstract configuration from conceptual or functional building blocks, is the most critical determinant of the product quality and cost. Quality concepts are the key to successful products. Visionary projects such as the Boeing 747 that stands out as a characteristic example of a well configured design concept. The plane is in service for over 35 years and no serious cause for replacement has emerged. This demonstrates that the configuration, dimensions, and other parameters (such as number of decks or the number of engines and their connection) that were determined at the conceptual design were adequate and far-reaching. In contrast to the general configuration, the particular details have changed as technology changed and there has not been any intrinsic difficulty to modernize them as modules. Boeing saved billions of dollars from the freedom not to develop a major platform over those years.

While the conceptual product design carries the majority of the value of the product compared to the detailed design, its decision-making is quite "soft": qualitative, and often *ad hoc* with few limited support tools or methods (e.g., brainstorming [6], morphological charts [11], and filtering morphological combinations [2]) [3][5].

The goal of this research has been the development of a comprehensive method that is domain independent and flexible in its ability to incorporate new business decisions such as outsourcing product design or intellectual property policy [8]. The method should be quite simple, in the spirit of QFD [1], enabling its use by diverse engineering teams. We call the method *SOS: Subjective Objective System* following the first metaphor we discuss next.

Several mathematical modeling metaphors capture the essence of SOS.

1. **Solution to differential equations**: the solution is composed of a homogeneous part and a particular, specific part. In our case, this principle translates to separating the **objective** (homogeneous part) and **subjective** concept solutions.
2. **Taylor series expansion**: the method uses detailed information only when necessary. Otherwise, simpler information structures are used. In our case, this translates to modeling the objective part with one layer since it is practically sufficient and the subjective part with several layers. The several layers collapse to one layer if there is not interaction between the geometry elements.
3. **Decomposition**: large problems can be simplified by decomposing them into sub problems. This relates to the previous item. Instead of reasoning with many criteria and preferences in one level, SOS allows to model specific items and combine then to the complete picture.
4. **Emergent complex behavior**: small modeling units contribute to precise overall model where the contribution of each is not easily discerned (e.g., Neural network modeling, ant-based algorithms). The capability of the overall model arises from the interactions between the simple units. In SOS, evaluations of influences or interactions are very simple, but our experience demonstrates that thus far are sufficient.

In this research, we have followed mainly a case study methodology [7][10]. We have put the method to work on a variety of real design problems ranging from miniature, high accuracy opto-mechanical systems, up to very large transportation equipment. We have also conceptually checked its applicability in diverse areas such as service (e.g., configuring a new banking service) and press (e.g., designing a new journal) industries.[1] In addition to leading to optimal concepts, SOS use in various design review meetings (preliminary design review, etc.) as a means of presentation and explanation was followed by focused discussion, easy concept approval, and overall customer satisfaction. We are in the process of checking the method with highly skilled experienced designers in about ten different industries.

This paper describes SOS – a subjective objective system for generating optimal product concepts. The method integrates information about the market, organization, and technology, and outputs the best concept configuration addressing the market opportunity. The method is demonstrated on a realistic case study.

2 Optimal concept generation

This section presents the method for optimal concept generation. First, we briefly define key terms. Subsequently, we introduce the method composed of two parts: the objective part and the subjective part.

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[1] The method has been in regular use by the second author in his design firm Ziv-Av Engineering[1] for several years and continues to enjoy feedback from its practical use. In order to appreciate the context in which the method has been used, see: www.zivaneng.com.

2.1 Definitions

Customer characteristics are product properties that are specified by the customer or the product users.

Designer characteristics are product properties used by designers to describe the design solution.

An optimal objective product concept is the best product concept that can be found without taking into account any resource, organization, or issues such as maintenance, assembleability, etc. The only governing aspect is functionality.

An optimal subjective product concept is the best product concept that is independent of functionality, but addresses all contextual aspects such as manufacturability, simplicity, cost, etc.

A decision layer is a part of the subjective (or objective[2]) concept formulation that organizes the relevant information in relation to the layer topic (e.g., product simplicity) and contributes a term to the subjective (objective) product concept formulation.

Constraints are limitations placed on the use of various combinations of building blocks when creating the product concept (see Section 2.3).

An optimal concept is formed by combining the formulations of the objective and subjective product concepts and solving it.

2.2 Method outline

SOS is formulated as a maximization problem, where a function that includes all contributions, objective and subjective is formulated and maximized subject to constraints. Both solutions can be formulated using several layers, each addressing a single customer or an engineering characteristic; nevertheless, based on our experience (and following the 2nd metaphor), the objective part can be simplified to a single layer. We describe SOS in this simplified version due to space limitations. SOS allows constructing the optimal concept for each layer and contrasting it with the overall optimal concept.

2.3 The objective solution

The objective solution is formulated in the first layer that is comparable to the main room of the House of Quality [1]. It records the contribution of product concept elements to attaining customer characteristics. It also records the mutual constraints between the concept elements. If we optimized the quality to customers, we would get the best product concept satisfying the intended function, disregarding any contextual aspect.

A matrix C connects between the functional parameters D_j and customers' characteristics P_i, see Figure 1. One important difference between SOS and QFD is that in QFD the D_j are engineering parameters of the product and here they are possible ways to realize these parameters (i.e., functional parameters). The matrix entries C_{ij} depict the contribution of functional parameter D_j towards satisfying customer characteristics P_i. The contribution of all functional parameters is given in Equation (1).

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[2] As we see later, practically, we use layers only in the subjective concept generation. Following the 2nd mathematical metaphor, this is acceptable.

$$\begin{array}{|ccc||c|}
D_1 & D_j & D_n & \\
\hline
C_{11} & & C_{1n} & P_1 \\
 & C_{ij} & & P_i \\
C_{m1} & & C_{mn} & P_m \\
\hline
\end{array}$$

Figure 1: Arrangement of data for generating the objective concept

$$P_i = \sum_{j=1}^{n} C_{ij} \cdot D_j , i = 1, \ldots , m \tag{1}$$

Each customer characteristic contributes to the total quality:

$$Q_i = W_i \cdot P_i \tag{2}$$

The total quality of the objective product concept is given by:

$$Q = \sum_{i=1}^{m} Q_i = \sum_{i=1}^{m} W_i \sum_{j=1}^{n} C_{ij} \cdot D_j \tag{3}$$

The best product configuration is the one that maximizes the quality for the customer subject to the constraints that exist between the different possible components.

$$\begin{gathered} \max Q \\ \text{subject to:} \\ g_l\left(D_1, \ldots , D_n\right) \overset{\le}{\underset{\ge}{=}} b_l , l = 1, \ldots , R \end{gathered} \tag{4}$$

The constraints represent relationships between the functional parameters or components. As seen on the following examples and based on numerous real projects, we can represent all the constraints we currently foresee as linear numerical expressions making them easily handled by linear programming. For example, consider the two following constraint types:

Mutual exclusiveness: If three components D_1, D_2, D_3 compete to be incorporated in the product and only one is selected then the constraint: $D_1 + D_2 + D_3 = 1, D_j = 0,1, j = 1,2,3$, makes sure that only one would be selected for the design concept.

Functional necessity: When component A must be selected if component B is selected we get $A - B \geq 0$. If the necessity works in both ways, the constraint becomes $A - B = 0$.

In summary, the objective function and the constraints are linear; therefore, this problem can be easily solved using various methods, e.g., Simplex. If the design variables are integers, as in the example constraint above and as we present later, the problem could be solved by Integer Programming.

2.4 The subjective solution

The subjective solution is modeled by a set of layers, each reflecting a particular aspect of the context of the product and manufacturer. Modeling an aspect by a separate layer allow greater precision in modeling the interaction between the parts that are candidates for the concept. For contextual aspects such as cost or simplicity, such interactions are highly important. These layers are reminiscent of the House of Quality roof; however, they are square, potentially asymmetric, matrices [4]. If we separately optimize each layer, we could get the best concept due to this aspect. Upon combining the information from all subjective layers, we obtain the best concept that matches the particular organization capabilities and context but is indifferent to functionality.

Figure 2 shows the information required for this optimization. In the middle of Figure 2, we write the matrix DPC_{ij}. Its diagonal depicts the direct contribution that component D_j has on the direct production cost (DPC). The *higher* values represent *lower* cost to be compatible with the maximization formulation in Equation (4). Off diagonal terms $DPC_{ij}, i \neq j$, represent the contribution that the pair of components i, j has on that cost. For example, front wheel drive is more expensive than rear wheel drive but cheaper than the combined drive; therefore, $DPC_{11} = 2$, $DPC_{22} = 1$, and $DPC_{33} = 3$. A combination of a longitudinal engine and a front wheel drive is more expensive than the combination between transverse engine and front wheel drive; therefore, $DPC_{61} = DPC_{16} = 1$ and $DPC_{71} = DPC_{17} = 2$. We call the information in Figure 2 the DPC $layer$.

$$\begin{array}{c|ccc|c} & D_1 & D_j & D_n & \\ \hline D_1 & DPC_{11} & & DPC_{1n} & V_1 \\ D_i & & DPC_{ij} & & V_j \\ D_n & DPC_{m1} & & DPC_{mn} & V_n \end{array}$$

Figure 2: Arrangement of data for generating the subjective concept of direct production cost

The contribution of the parameters D_j toward DPC can be calculated from Equations (5) and (6). Practically, if a pair is present in the configuration, its corresponding values are added to the cost. The contribution to DPC of component j and its interactions is:

$$V_j = D_j \cdot \sum_{k=1}^{n} DPC_{jk} \cdot D_k, j = 1, \ldots, m \tag{5}$$

and the total contribution sums to:

$$DPCP = \sum_{j=1}^{n} V_j = \sum_{j=1}^{n} D_j \cdot \sum_{k=1}^{n} DPC_{jk} \cdot D_k \tag{6}$$

In general, we may have as many layers in the calculation depicting different issues such as: design for assembly, design for maintenance, and cost. Each of them needs to be modeled in a similar way to the one in Figure 2. Figure 3 is one such representative layer.

For each layer l, its contribution towards the cost is given in Equation (7).

$$LC_l = \sum_{j=1}^{n} V_{lj} = \sum_{j=1}^{n} D_j \cdot \sum_{k=1}^{n} SC_{ljk} \cdot D_k \tag{7}$$

$$\begin{array}{c|ccc|c} & D_1 & D_j & D_n & \\ \hline D_1 & SC_{11} & & SC_{1n} & V_1 \\ D_i & & SC_{ij} & & V_j \\ D_n & SC_{m1} & & SC_{mn} & V_n \end{array}$$

Figure 3: Arrangement of data for generating the subjective concept

2.5 Combining objective and subjective solutions

We assume an additive value of objectives. Therefore, we can sum the contribution of all layers into one subjective solution given an assignment of relative weight among them. The total subjective cost (TSC) would be:

$$TSC = \sum_{l=1}^{L} w_l \cdot LC_l \tag{8}$$

Finally, the objective function of the overall concept design optimization, including the objective and subjective parts, is:

$$\begin{gathered} \max\left(w_0 Q + \sum_{l=1}^{L} w_l \cdot LC_l \right) \\ \text{subject to:} \\ g_l\left(D_1,\ldots,D_n\right) \overset{\le}{\underset{\ge}{=}} b_l, l = 1,\ldots,R \text{, and } \sum_{l=0}^{L} w_l = 1 \end{gathered} \tag{9}$$

The result is a solution that makes a compromise between all layers.

3 Designing a Police Intercity Tour Vehicle

Problem description

The following example demonstrates the use of the framework in a realistic project of designing a Police Intercity Tour Vehicle. There are several kinds of police vehicles for different purposes: traffic control, town activity, crew transportation, intercity tours etc. In this example, we describe the intercity vehicle optimal configuration generation. The vehicle is to be used for a crew of 8 policemen: a driver, a commander sitting at the front and 6 policemen at the rear compartment. It has to enable the crew to arrive quickly to various places and incidents and to operate from and around the vehicle. The vehicle has to be a modification of an existing minivan model, in this example from the Peugeot-Citroen range.

In more details, the Customer Requirements are (see Figure 4, column (b)):

1. Good handling & stability
2. Good comfort (Min. jostling)
3. High accidents safety
4. Good off-road maneuverability
5. Relatively minimal mines damaging
6. Minimal turning radius
7. Good driver's field of vision
8. Easy crew entrance and exit
9. Safe entrance and exit under fire
10. In-vehicle fighting ability
11. Good crew field of vision
12. Minimal footprint
13. 13.Easy equipment loading/unloading
14. 14.Easy maintenance

In general automotive design, the available options for creating concepts are:

1. Front engine
2. Rear engine
3. Driver location before front wheels
4. Driver location behind front wheels
5. Front drive
6. Rear drive
7. Four wheel drive
8. Central transmission
9. Back door
10. Crew back-to-back facings sides
11. Crew facing front
12. Rigid axels
13. Independent suspensions

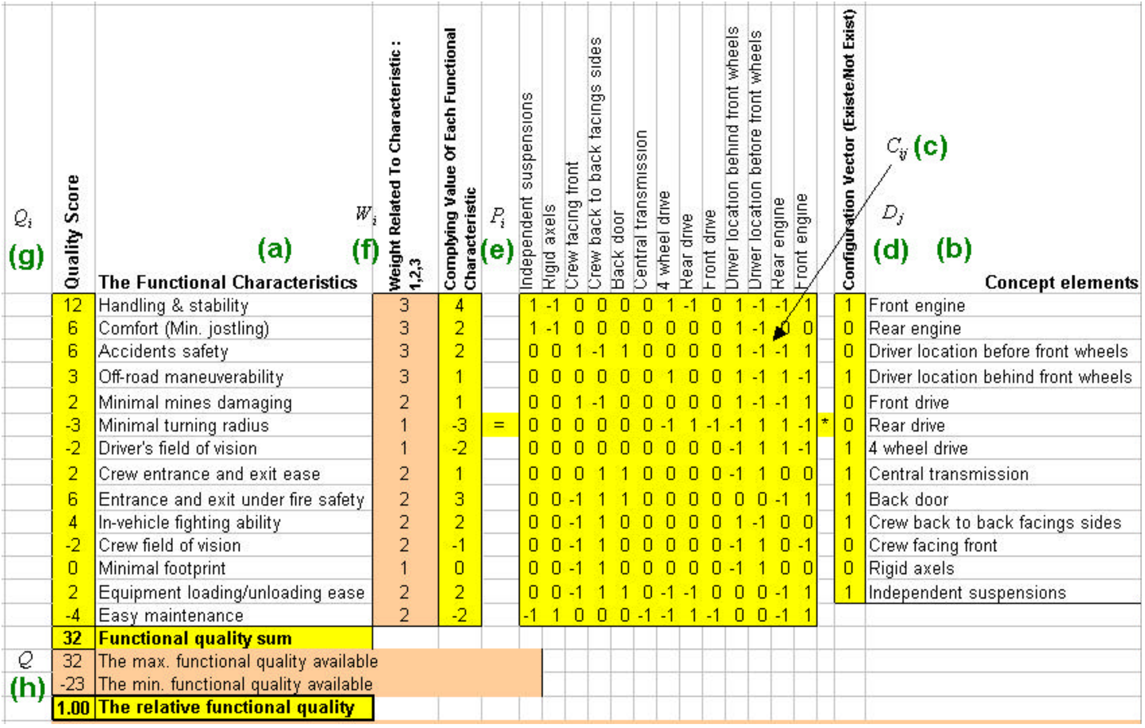
The constraints for the legal choices and combinations between the design options are:

1. Front engine **OR** rear engine
2. Driver before front wheels **OR** behind front wheels
3. Front drive **OR** rear drive **OR** 4-wheels drive
4. 4-wheels drive **FORCES** central transmission and vice versa
5. Rigid axels **OR** independent suspensions Crew facing sides **OR** facing front
6. Crew facing sides **FORCES** back door
7. Not possible rear engine **AND** crew facing sides
8. Not possible rear engine **AND** back door

Objective concept generation

Let us consider the requirement "good handling & stability" as an example of translating the information into the mathematical model. In order to best satisfy it, we prefer long wheelbase, under-steer characteristic, minimum horizontal moment of inertia, and minimum sensitivity to low tires-road friction coefficient. Therefore, the front engine gets $D_1 = 1$ and the rear gets $D_2 = -1$, the driver location before front wheels gets $D_3 = -1$, and behind them gets $D_4 = 1$. The existence of a central transmission, the arrangement of the crew and the doors location are irrelevant so they get 0 value.

The remaining choice is the relative importance of the requirements. The information for the optimal objective concept formulation is given in Figure 4. The figure includes the Equations notations and it has the same structure as in Figure 1. The result (item (h) in the Figure) also specifies how far is the generated concept from the best functional concept.



Q_i (g)	Quality Score	(a) The Functional Characteristics	W_i (f) Weight Related To Characteristic : 1,2,3	Complying Value Of Each Functional Characteristic	P_i (e)	Independent suspensions	Rigid axels	Crew facing front	Crew back to back facings sides	Back door	Central transmission	4 wheel drive	Rear drive	Front drive	Driver location behind front wheels	Driver location before front wheels	Rear engine	Front engine		C_{ij} (c) Configuration Vector (Existe/Not Exist)	D_j (d) (b) Concept elements
	12	Handling & stability	3	4		1	-1	0	0	0	0	1	-1	0	1	-1	-1	1		1	Front engine
	6	Comfort (Min. jostling)	3	2		1	-1	0	0	0	0	0	0	0	1	-1	0	0		0	Rear engine
	6	Accidents safety	3	2		0	0	1	-1	1	0	0	0	0	1	-1	-1	1		0	Driver location before front wheels
	3	Off-road maneuverability	3	1		0	0	0	0	0	0	1	0	0	1	-1	1	-1		1	Driver location behind front wheels
	2	Minimal mines damaging	2	1		0	0	1	-1	0	0	0	0	0	1	-1	-1	1		0	Front drive
	-3	Minimal turning radius	1	-3	=	0	0	0	0	0	0	-1	1	-1	-1	1	1	-1	*	0	Rear drive
	-2	Driver's field of vision	1	-2		0	0	0	0	0	0	0	0	0	-1	1	1	-1		1	4 wheel drive
	2	Crew entrance and exit ease	2	1		0	0	0	1	1	0	0	0	0	-1	1	0	0		1	Central transmission
	6	Entrance and exit under fire safety	2	3		0	0	-1	1	1	0	0	0	0	0	0	-1	1		1	Back door
	4	In-vehicle fighting ability	2	2		0	0	-1	1	0	0	0	0	0	1	-1	0	0		1	Crew back to back facings sides
	-2	Crew field of vision	2	-1		0	0	-1	1	0	0	0	0	0	-1	1	0	-1		0	Crew facing front
	0	Minimal footprint	1	0		0	0	-1	1	0	0	0	0	0	-1	1	0	0		0	Rigid axels
	2	Equipment loading/unloading ease	2	2		0	0	-1	1	1	0	-1	-1	0	0	0	-1	1		1	Independent suspensions
	-4	Easy maintenance	2	-2		-1	1	0	0	0	-1	-1	1	-1	0	0	-1	1			
	32	**Functional quality sum**																			
Q	32	The max. functional quality available																			
(h)	-23	The min. functional quality available																			
	1.00	**The relative functional quality**																			

Figure 4: Police Car –information for deriving the optimal objective concept: (a) functional characteristics, (b) concept elements, (c) the relation C_{ij}, (d) the parameters values D_j, (e) the P_i values (Equation 1), (f) the weight W_i, (g) the result of Equation 2, and (h) the quality Q (Equation 3)

The best concept for satisfying the objective requirements is (column (d)):

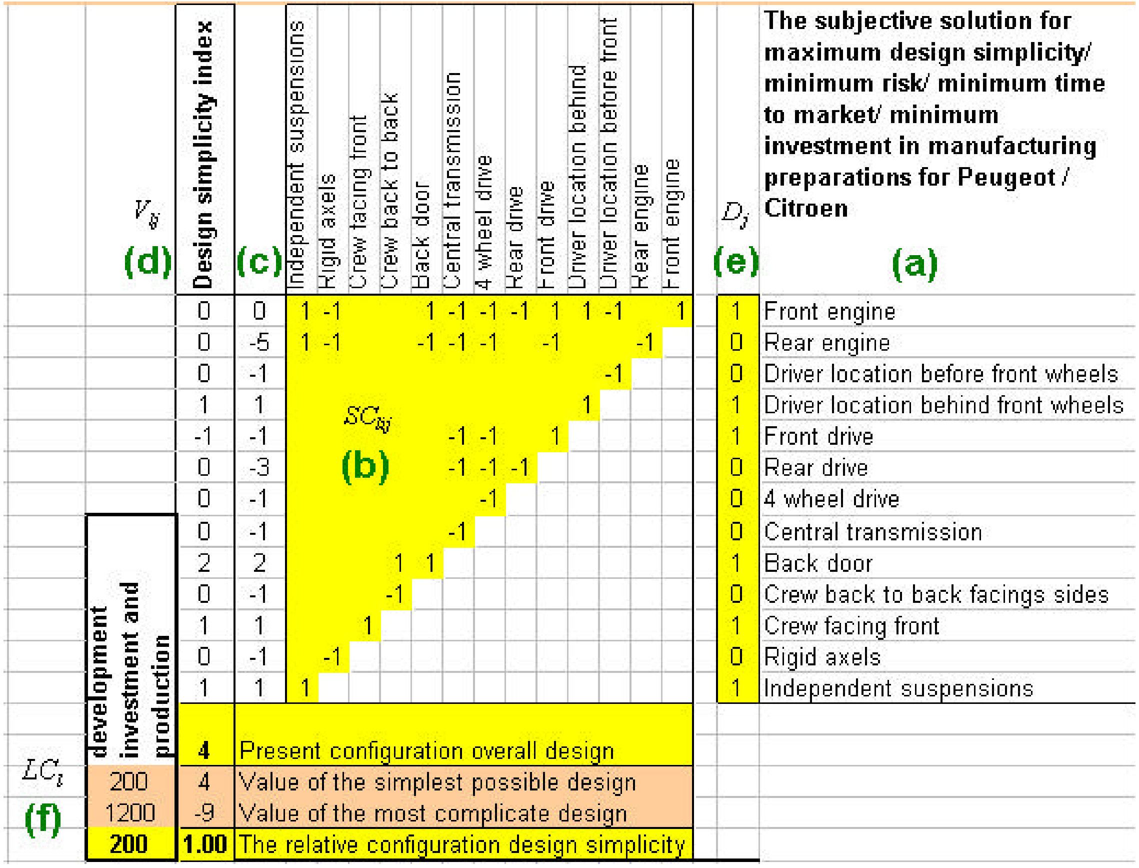
Front engine
Driver location behind front wheels
4 wheel drive
Central transmission
Back door
Crew back-to-back facings sides
Independent suspensions

Subjective concept generation

Assume we are interested in the following subjective layers:

1. The subjective solution for maximum design simplicity/ minimum risk/ minimum time to market/ minimum investment in manufacturing preparations for Peugeot-Citroen.
2. Minimal production cost for Peugeot-Citroen.

For example, for the first layer, for Peugeot-Citroen, front engine is simpler compared to the rear engine therefore, $SC_{111}=1$ and $SC_{122}=-1$. The combination of front engine and a driver location ahead the front wheels is complicated, therefore, $SC_{113}=-1$, and its combination with driver location behind the front wheels is simpler therefore, $SC_{114}=1$. For Peugeot-Citroen the combination of a front engine and front drive is an existing system, its combination with rear drive needs special development, while a four-wheels drive is generally complicated, therefore, $SC_{115}=1$, $SC_{116}=-1$, and $SC_{117}=-1$. Whenever the combination is irrelevant, the value is set to 0. The information for deriving the optimal subjective concept reflecting the desire to maximize design simplicity etc. is given in Figure 5.



	V_{lj} (d)	Design simplicity index	(c)	Independent suspensions	Rigid axels	Crew facing front	Crew back to back	Back door	Central transmission	4 wheel drive	Rear drive	Front drive	Driver location behind	Driver location before front	Rear engine	Front engine	D_j (e)	The subjective solution for maximum design simplicity/ minimum risk/ minimum time to market/ minimum investment in manufacturing preparations for Peugeot / Citroen (a)
		0	0	1	-1			1	-1	-1	-1	1	1	-1		1	1	Front engine
		0	-5	1	-1			-1	-1	-1		-1			-1		0	Rear engine
		0	-1											-1			0	Driver location before front wheels
		1	1			SC_{lij}							1				1	Driver location behind front wheels
		-1	-1						-1	-1		1					1	Front drive
		0	-3			(b)			-1	-1	-1						0	Rear drive
		0	-1							-1							0	4 wheel drive
		0	-1						-1								0	Central transmission
		2	2				1	1									1	Back door
		0	-1				-1										0	Crew back to back facings sides
		1	1			1											1	Crew facing front
		0	-1		-1												0	Rigid axels
		1	1	1													1	Independent suspensions
	development investment and production	4	Present configuration overall design															
LC_l	200	4	Value of the simplest possible design															
(f)	1200	-9	Value of the most complicate design															
	200	1.00	The relative configuration design simplicity															

Figure 5: Police Car – information for deriving one of the optimal subjective layers: (a) concept elements, (b) interactions between elements SC_{lij}, (c) intermediate calculation, (d) the V_{lj} values (Equation 7), (e) the concept elements values D_j, and (f) the quality LC_l (Equation 8) and also the investment cost

Maximizing LC_1 (Equation 8) will lead to the simplest concept for Peugeot / Citroen with the minimal investment cost:

Front engine	Back door
Driver location behind front wheels	Crew facing front
Front drive	Independent suspensions

In the same way, we can generate the optimal solution for each subjective layer and expect to get a variety of concepts, each geared toward its layer's goal. In this example, the optimal subjective configuration for achieving minimum mass production cost is:

Front engine
Driver location before front wheels
Rear drive
Back door
Crew back-to-back facings sides
Rigid axels

The overall best concept is one that maximizes the objective and subjective layers simultaneously while satisfying the constraints. It will change depending on the preferences regarding the importance of the different layers. In the present example, the overall design concept is:

Front engine
Driver location behind front wheels
Front drive
Back door
Crew back-to-back facings sides
Independent suspensions

The model shows that the overall design concept matches the subjective concept that is simplest for Peugeot-Citroen. Indeed, Peugeot-Citroen can produce such a car by modifying an existing model, e.g., model 807. This demonstrates the ability of the model to capture accurate (even if coarse) information and obtain good results that are consistent with reality. Furthermore, if we generated such layers for other manufacturers, we could have gotten the best concept for each manufacturer. This would have given us significant information for deciding which manufacturer would receive the contract.

Since SOS not only assist in concept generation but also creates the concept, we can run sensitivity analyses on different evaluations and obtain the sensitivity of the concept. Moreover, since the concept is an integration of various building blocks, we can assess the sensitivity of each with respect to different evaluations. For example, it turns out that front engine and back doors are invariants of any evaluation. In addition, for a large range of weight w_l in Equation 8, the Driver location behind front wheels, Crew back-to-back facings sides, and the Independent suspensions are invariants. This suggest that the present concept is quite robust.

4 Conclusions

SOS has been developed over years of practice and research and evolved into a method for generating optimal product concepts. The method builds concepts out of available building blocks and has the following properties:

1. The method is applicable to many domains (including outside engineering, such as: design a new journal or a banking service).
2. The method is easy to understand and execute.
3. The method is flexible and can accommodate new business issues such as outsourcing. Layers could be added to it to enrich any problem representation. Each layer could use the scale that best fits its semantics (e.g., $ for cost, time for life cycle, etc.).
4. The method works well in industrial settings as practiced by the first author.

We plan to continue evolve SOS and expand its capabilities. We also intend to approach its evaluation using different research methods in the near future.

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