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Instant Set-Based Design, an Easy Path to Set-Based Design

Mikael Ström[a]*, Dag Raudberget[b], Göran Gustafsson[b]

[a]*Swerea IVF AB, PO Box 104, SE-431 22 Mölndal, Sweden*
[b]*Chalmers University of Technology, Department of Product and Production Development, SE-412 96 Gothenburg, Sweden*

* Corresponding author. +46-70-7806023; fax: +46-31-276130. *Email address:* mikael.strom@swerea.se

Abstract

A simplified variant of Set-Based Design (SBD) was created. It was combined with the creative methods 6-3-5 and the Gallery method as well as the systematic method morphological matrix to generate solutions. This made it possible to introduce SBD in one day, which has been verified by tests on design problems at industrial firms. The methodology, Instant Set-Based Design (ISBD), was perceived easy to understand and was well received by the designers. The introduction of it was less cumbersome compared to the full version of SBD. The conclusion is that the developed methodology works as intended with good results.

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Keywords: Set-Based Design; Lean; Product Development; Design; Creative Methods

1. Introduction

Several authors prescribe a process with common steps to take when developing products. Descriptions are found in literature by Pugh [1], Ulrich and Eppinger [2], Pahl et al. [3] among others.

A development methodology that uses a different approach compared to the processes above is Set-Based Concurrent Engineering (SBCE) [4, 5], or, more generally, Set-Based Design (SBD). One of its characteristics is to explore the design space by developing multiple solutions and rejecting iterations as a prescribed means to improve task descriptions, requirements lists, concepts and designs. SBD instead uses a converging, parallel process with proven feasibility to narrow descriptions of requirements, designs and manufacturing systems to arrive at a final solution, see Figure 1. One means in SBD is to produce reusable knowledge to prove feasibility. It has received positive attention and some authors claim that SBD and related practices from Lean Development are four times more productive than conventional development models [4, 5].

SBD is however challenging to introduce for several reasons. It is usually considered incompatible with traditional phased project models [5, 6], which are common ways to organize an industrial development process. Another challenge not described in the literature is how to generate the multiple alternatives that are central in SBD. Furthermore, there is little guidance on how to deploy SBD in practice.

To overcome the abovementioned difficulties, a new simplified approach coined Instant Set-Based Design (ISBD) is presented where the SBD process is streamlined and supplemented with methods for creativity, systematic concept generation and design evaluation. The objective of this research is to develop a methodology to present SBD in one day, thereby facilitating an easier introduction of the methodology and support the existing design processes.

The research question we pose is: *Can a Set-Based Design process combined with creative and systematic methods for concept generation be efficiently introduced in an industrial environment in only one day?*

2. State of the art

The state of the art is limited to the field of Set-Based Design, and to established creative and systematic methods that are suitable for industrial settings, i.e. possible to perform within a short period of time.

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2.1. Set-Based Concurrent Engineering and Set-Based Design

In conventional development as described by Ward & Sobek [4], here called Point-Based Design (PBD) as stated by Ward et al. [15], a single design solution is selected early, when the knowledge and understanding of the problem is low. This single design is then iteratively re-worked and improved until a feasible solution is arrived at.

Set-Based Concurrent Engineering has received positive attention for its emphasis on the importance of studying alternative design solutions and variations of them referred to as “sets of solutions”, hence Set-Based. SBCE is also known for its distinctive process of parallel evaluation and gradual narrowing of the requirement description, the design space and the manufacturing system design space. See Figure 1.

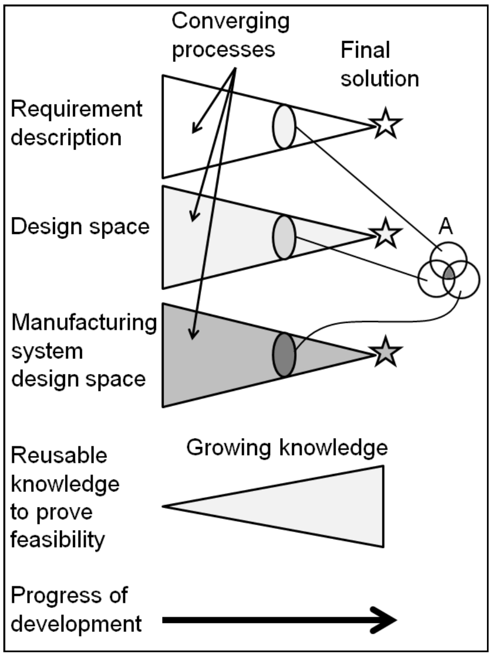

Figure 1. In SBCE, the requirement description, the design space and the manufacturing system design space are gradually narrowed in parallel as more knowledge is gained. After Ward [15]. In A integration is done by intersection of feasible regions.

It enables designers to reason about regions of the design space by communicating the constraints of different solutions, and it has a convergence process for arriving at a final design in parallel with increasing understanding of the problem through the creation of reusable knowledge. Set-Based Design is the activities used to designing according to the principles of SBCE. The principles are given in Table 1.

In SBD [7], no single design solution is selected in the early phase of development. Instead, convergence towards a solution is achieved by testing and learning about the different alternatives. Unfeasible alternatives are eliminated and feasible regions in the design space are narrowed based on facts from tests or other sources of validated knowledge. SBD emphasizes learning and the creation of reusable knowledge [4].

Table 1: The three principles of Set-Based Concurrent Engineering. After Sobek et al. [16].

Principle	Stage	Description
I	Map the design space	Define feasible regions Explore trade-offs by designing multiple alternatives Communicate sets of possibilities
II	Integrate by intersection	Look for intersections of feasible sets Impose minimum constraint Seek conceptual robustness
III	Establish feasibility before commitment	Narrow sets gradually while increasing detail Stay within sets once committed Control by managing uncertainty at process gates

2.2. The 6-3-5 method

In design theory, Pahl et al. [3] present solution-finding methods. Two of these are intuitive methods: the 6-3-5 method and the Gallery method. In the 6-3-5 method, six participants each create three solutions to the problem and then pass them on to their respective neighbor, who further develops them. This goes on until the solution returns to the original creator and has been processed by the other five participants, hence the name 6-3-5.

2.3. The Gallery method

In the Gallery method [3], a group of persons work on the same problem by sketching solutions on separate sheets of paper. The sheets are then posted on a wall for all involved to see and discuss. A second round of solution creation and posting on the wall is then performed. The last activity is the selection step where promising solutions are identified.

The concept generation phase is described by Ulrich and Eppinger [2] as a five-step method in which team knowledge and creativity is one means of generating concepts. Tools in this are analogies, wish and wonder, related and unrelated stimuli, setting of quantitative goals and the Gallery method.

2.4. Morphological matrix

The morphological matrix was introduced by Zwicky, as reported by Pahl et al. [3]. It is a systematic presentation of information and data that illustrate the possible combinations of partial solutions that can make up overall solutions. An example is given in Table 2.

The partial solutions to a function are written on the same row in a matrix. The general idea is to generate one or several overall solutions by selecting one solution from each row which are compatible with each other.

Table 2. A morphological matrix for a mechanical transmission.

Function	Sub-solution 1	Sub-solution 2	..	Sub-solution n
Provide sealing	Labyrinth seal	Lip sealing		Xx sealing
Generate power	Linear motor	Asynchronous AC motor		Permanent magnet servo motor
Transform electrical power	Pulse width modulation	Variable frequency drive		Stepper motor controller
Transform mechanical power	Planetary gears	Rack and pinion		Cylindrical gears

2.5. Pugh's method for controlled convergence

Pugh's method aims at controlling the design convergence [1]. The centre of the method is the Pugh matrix that is used for design evaluation by comparing and selecting the most promising design among a set of alternatives. It is a relative evaluation using a datum, a reference solution to which the alternatives are compared as: better than "+", same as "S" or worse than "-" the datum with respect to different criteria. An example of a Pugh matrix is seen in Table 3.

Table 3: Pugh´s matrix. Adapted from [1].

Criteria	Concept	Concept 2	Concept 3
Criterion 1	D	S	+
Criterion 2	A	-	+
Criterion 3	T	+	S
Criterion 4	U	-	-
Criterion 5	M	+	S
No. of +		2	2
No. of -		2	1
No. of S		1	2

This relative comparison between individual properties of the design alternatives and the datum is an important feature of the method, since it is easier for humans to compare a solution to a datum than to evaluate a numeric score.

One approach to use Pugh's matrix in Set-based trials is presented by The Lean PPD project [8] that involved several industrial and academic partners throughout Europe. The authors use a Pugh matrix to evaluate concepts as part of the suggested methodology.

2.6. Conclusions from the literature study

Reflecting on the literature mentioned above, there is a lack of methodology for simplified SBD approaches. Current implementations of SBD in industrial environments all represent substantial costs and workload such as the processes described in the work of Al-Ashaab et al. [8] and Raudberget et al. [9, 10].

These implementations also lack support for the creative phases where SBD is combined with creative and systematic methods.

In a Set-Based perspective it is also questionable to select the *best* alternative among several. Furthermore, it is difficult to obtain hard facts to enable the selection of a future technical system without first designing, building or simulating it. In this research we therefore do the opposite; we use a Set-Based process with a Pugh matrix to *eliminate* weak alternatives. We call the latter an *inverse Pugh matrix*. Tangible reasons for elimination are easier to find compared to picking the best alternative, particularly at a stage when the knowledge about the different solution concepts is low.

The approach of eliminating weak alternatives is also applied to the Gallery method. As described by Pahl et al. [3], this method aims at selecting promising designs, but in the presented research it is instead used to identify inferior alternatives.

3. Method

The research process mainly followed the Design Research Methodology (DRM) for the development of design support [11]. DRM was however not applied in a strict sequence from stage I to stage IV, but rather performed in a non-linear fashion. The reason for this is that the ISBD methodology was not considered mature enough to be evaluated against the goals in a concluding *Descriptive study 2.* The process was therefore iterated between stages II and III until the result was satisfactory. The authors of DRM also state that the stages can be passed in a different sequence.

A literature study in the Research Clarification stage indicated that the introduction of SBD is a cumbersome process [14], and that there was therefore a need for the suggested support. Also the research question and preliminary goals were formulated. As a starting point for the empirical research a number of methods from the literature were collected into the initial support Variant A, thus forming the basis for the initial Prescriptive study.

The two Descriptive study 1 activities were developed as parts of workshops with industrial collaborators aiming at understanding the ISBD methodology to the extent that it is possible to identify which parameters are important for its success. The information collected from the workshops was used to analyze the usefulness of the ISBD methodology and thereby form the basis for the Prescriptive study where it is developed. For the first two iterations it was evident that the ISBD methodology needed to be further developed before being applied to a real industrial development project of Descriptive study 2.

3.1. Objectives and success indicators

The objective was to improve the ISBD methodology so that it could be introduced, learned and applied within one work day. To support the work, the research question in section one was stated together with the indicators of success given in Table 4.

Table 4. Indicators of successful research for ISBD.

Success indicators	Description
1	Do the methodology generate more ideas than the current way of working in the company
2	Do experienced engineers accept the methodology as a new way of working?
3	Do experienced engineers accept the results that the methodology generates?
4	Can the methodology be learned in a day?
5	Can a firm use the methodology without the support from researchers after that day?
6	Is it feasible to combine creative and systematic methods for concept generation to feed the ISBD process?

3.2. Case study setup

The study was a joint venture between industry, Chalmers University of Technology and SWEREA IVF AB as project manager. Information was collected through eight workshops, and by interviewing the participants. The setup is a multiple case study [12] of mechanical design comprising five main industrial design cases and three initial, slightly different cases. It differs from the description of Yin [12] in that it included a portion of action research [13], in which the researchers were actively involved themselves in the studied process. The reason for using action research was to develop, introduce and evaluate a new design methodology which the participants of the study did not have sufficient knowledge to apply on their own, i.e. without the support of the researchers.

3.3. Designs

The designs in cases 1, 4, 5, 6, 7, and 8 were a staircase (1), a door lock (4 and 5), a tilt lock of a steering column (6), a clamp to fix a fuel tube (7) and a case for a piece of consumer goods (8).

3.4. Collection of empirical material

In the Case 1 workshop, one researcher introduced the ISBD methodology, made observations and took notes. Cases 2 and 3 were held in a course context and were recorded by one researcher who also acted as a teacher. From a research point of view, the workshop environments were easy to monitor and thereby to evaluate the results from. Cases 4, 5, 6, 7 and 8 aimed at evaluating the ISBD methodology in a true industrial environment. Two researchers recorded cases 4, 6, 7 and 8. Case 5 was run independently by the firm without the presence of the researchers. Here, the data was collected retrospectively through oral communication. In Case 7, the Gallery method was excluded and instead a morphological matrix (MM) was introduced to combine creative and systematic methods to generate concepts to feed the ISBD process. Case 8 was similar to Case 7 with the difference that most of the theory in the first part of the ISBD methodology was transferred prior to the workshop. This made it possible to combine the 6-2-5 method, the Gallery method and an MM in the time frame of a working day.

One of the researchers was exchanged between sessions, so the total number of researchers having observed at least one workshop is three. The time between each switch in the 6-3-5 method, the number of solutions and the types of knowledge gaps discovered were recorded. Narratives in the form of sketches, Pugh matrices and MMs were also documented and photos were taken in each session. Each case was followed up by interviewing participants on how they perceived the workshop. A summary of the collection of empirical material is given in Table 5 below.

Table 5. The collection of empirical material described in chronological order. In total 56 persons has participated in the studies (* same 11 persons), (** without the gallery method).

Case no.	Participants (P)	No. of P	Variant	Application	Setting
1	Industrial representatives in research project	8	A	Industrial	Research institute
2	Industrial representatives	10	B	LPD course	Conference facilities
3	Line managers	10	B	LPD course	Firm A
4	Designers	11*	B	Industrial	Firm B
5	Designers	11*	B	Industrial	Firm B
6	Designers	6	C	Industrial	Firm C
7	Designers	6	D**	Industrial	Firm D
8	Designers	5	D	Industrial	Firm E

4. The Instant Set-Based Design methodology

After going through four successive variations, the resulting ISBD methodology is based on the following steps:

1) A brief introduction to SBD, the 6-3-5 method, the Gallery method, MM and the inverse Pugh matrix.
2) Presentation of the design problem and required functionality of possible solutions. All participants should be well informed of the problem at hand in order to be able to contribute to the solution of it.
3) Generation of solutions by the 6-3-5 method.
4) Presentation of the solutions by posting them on a wall.
5) Collaborative analysis of how each function is realized in each concept.
6) Elimination of solutions by identifying weaknesses in them. Issues were written on post-it notes and solutions with several weak points were removed and stored in the design repository.
7) Application of the Gallery method to remaining solutions.
8) Using an MM for all concepts to try to generate more solutions by cross-fertilization.
9) Posting of improved solutions on the wall and study of them by means of an inverse Pugh matrix.

10) Identification of knowledge gaps, to fulfill the required functionality, and ways to bridge them.
11) Elimination of the least feasible solutions based on the results from the inverse Pugh matrix.

Since the ISBD methodology is a bundle of design methods, the design team is required to familiarize itself with these theories prior to the workshop. ISBD aligns with SBD by using the first two principles of SBCE [Sobek et al. 1999], see Table 1. It however prepares for the use of principle 3 in step 10 above by indicating what knowledge is needed and how to acquire it to prove feasibility of solutions. In step 6, weak solutions are stored in a design repository to save the knowledge gained for later use, and this too is similar to SBD [4]. In Table 6, we compare the features that are the core of ISBD to SBD and PDB. PBD could of course in principle consider multiple solutions too, but the essence of PBD [4, 15] is decidedly *not* to do that.

Table 6: Comparison between ISBD, Set-Based Design (SBD) and Point-Based Design (PBD). Y = yes, N = no.

Feature	ISBD	SBD	PBD
Starts with multiple solutions	Y	Y	Y
Integrates creative and systematic methods to generate multiple solutions	Y	N	N
Simultaneously explores multiple solutions in a converging process	Y	Y	N
Selects the most promising solution	N	N	Y
Continuously eliminates inferior solutions	Y	Y	N
Has a fixed specification	Y	N	Y
The specification is based on intervals	N	Y	N
Iterates to correct failures as a typical means	N	N	Y
Has convergence built into it	Y	Y	N
Early detection of knowledge gaps	Y	Y	N
Takes advantage of late design decisions	Y	Y	N
On the spot exploration of multiple solutions	Y	N	N
Explores concepts through testing	N	Y	Y
Facilitates sharing of information, ideas and knowledge	Y	Y	N
Can continue as a true SBD process	Y	Y	N

5. Discussion

Judging by the success criteria of Table 4, the results indicate that the applications of the methodology were successful in all eight cases. Cases 1-6 indicate that ISBD fulfills the criteria 1-5. Cases 7-8 indicate that criterion 6 is fulfilled, and in both cases the MM gave birth to one new creative solution. In cases 7 and 8 however, the addition of the MM made it hard to finish the workshop within an eight hour work day. Even though the MM can be established within a relatively short time (30-60 minutes), the Gallery method was excluded in case 7 to also allow the effect of the MM to be evaluated. In case 8, slightly more than eight hours was used. The workshop participants were prepared in a theory session prior to the day of the workshop and all methods of ISBD could therefore be included in the one-day workshop.

5.1. All cases involved participants from the industry. Five of them took place in industrial settings, and four are true industrial applications that prove the capability of ISBD. Answer to the research question

The research question "*Can a Set-Based Design process combined with creative and systematic methods for concept generation be efficiently introduced in an industrial environment in only one day?*" can be answered in the following ways:

The results show that the ISBD methodology is feasible for introducing parts of SBD in the form of a converging design process based on multiple sets of design solutions and a successive elimination of inferior solutions.

The results are valid for mechanical design problems and no information on how ISBD supports other types of settings are possible to extract. However, the nature of the methodology indicates that any problem that can be described graphically in sketches or flow diagrams should be suitable for the approach.

The goal was to effectively introduce the methodology in industry, and in case 5 the firm applied ISBD independently after the workshop. This indicates that a firm can use ISBD without the support from researchers after one day.

To implement the complete ISBD methodology, more than an eight-hour workday is needed, and in that sense the methodology did not fulfill the intended goal. In case 8, the first part of the ISBD methodology (step 1) was given prior to the workshop for scheduling reasons, which consumed 2 hours of time. The remaining part of the full ISBD (step 2-11) could therefore be applied and completed in one work day.

At present, either the Gallery method or the morphological matrix must be excluded in order to reach the eight-hour mark. This was successfully done in case 7 (see Table 5), where the Gallery method was excluded. Both methods have their specific ways of contributing to the generation of solutions. The Gallery method is a visual collaborative creative process that enables the team to think as a group. The morphological matrix is a systematic method that helps creating new combinations that are not conceived by pure creative thinking. Ideally, both methods should be used in a workshop, and how to reach this goal is a part of the future work to further develop the suggested methodology.

5.2. Reliability

The observations were conducted by three researchers. The methodology had a high acceptance among the participants. Since these were experienced engineers, the methodology appears to be useful in their context. In total 56 experienced design engineers tested the methodology at different maturity levels on eight different occasions. There was no notable disagreement in the research group or among the test persons regarding the results from each test case, rather the opposite.

The participants stated that the work was interesting, useful and inspiring, and there is no doubt that the methodology can be used as intended.

5.3. Generality

The ISBD methodology was tested in six different industrial mechanical design cases at five different firms. In cases 4, 5, 6, 7 and 8, in which the methodology had reached a high maturity level, the test persons were experienced designers at comparable competence levels. In case 5, one of the firms has continued to use ISBD themselves after the introduction, with success. The results of the described work were also presented to a reference group of 14 persons (in a lean product development interest group) from eight different firms. The impression of the group was that the methodology was worth trying. This strengthens the conclusion that ISBD works well in the domain where it was tested and applied. It has so far only been tested in a Swedish cultural context though, which may limit its generality.

6. Conclusions

From the abovementioned, the following conclusions are drawn:

- Instant Set-Based Design (ISBD) works well in an industrial environment applied to mechanical design problems
- The limited version of ISBD can be completed in one work day of eight hours
- ISBD can be used to start up the implementation of Set-Based Design
- ISBD helps industrial firms to implement Set-Based Design

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