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DEVELOPMENT OF A METHODOLOGY TO IMPLEMENT SET-BASED DESIGN IN A DAY

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1. Introduction

Industrial product development often follows a formal design process that is based on different schemes. Formal design processes are important since they transform the development activities from heuristic into a structured, repeatable process. Several authors prescribe common steps to be taken when developing products, which are found in literature by Ulrich and Eppinger [2012], Pugh [1991] and Pahl et al. [2007], among others.

A development methodology that uses a different approach compared to the processes above is Set-Based Concurrent Engineering (SBCE) [Morgan and Liker 2006], [Ward and Sobek 2014] and Set-Based Design (SBD). It is described as a new way for engineering design and one of its characteristics is to explore the design space by developing multiple solutions. It has received positive attention and some authors claim that SBD and related practices from Lean Development are four times more productive than traditional development models [Morgan and Liker 2006], [Ward and Sobek 2014].

SBCE is however challenging to introduce for several reasons. It is usually considered incompatible with traditional phased project models [Morgan and Liker 2006], [Kennedy et al. 2008], [Ward and Sobek 2014], which are common ways to organize an industrial development process. Another challenge not described in the literature is what methods and strategies to use in order to generate the multiple alternatives that are of vital importance to SBD. Furthermore, there is little guidance on how to deploy SBD in practice. Current theory does not explain this in detail.

To overcome the abovementioned difficulties, a new simplified approach coined Instant Design (ISBD) is presented where an SBD process is streamlined and supplemented with methods for creativity and design evaluation. The purpose of this research is to improve engineering design processes in industry by supporting them with SBD. The objective is to develop a methodology to introduce SBD in one day, thereby facilitating an easier implementation of the methodology.

2. State of the art

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

2.1 Set-Based Concurrent Engineering and Set-Based Design

Set-Based Concurrent Engineering has received positive attention for considering alternative design solutions and exploring their behaviour when the design variables are changed. It e.g. emphasizes the questions of where the limits of the proposed designs and techniques are, and what the trade-offs between different properties look like, both which are very important to answer in order to arrive at a

successful final design. SBCE also enables designers to reason about regions of the design space by communicating the constraints of different solutions, and it has a distinctive convergence process to arrive at a final design.
SBD is the collection of activities undertaken and tools used in the process when designing according to the principles of SBCE. The principles are given in Table 1.

Table 1. The three principles of Set-based Concurrent Engineering after Sobek et al. [1999]

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

An important difference between SBD [Ward and Sobek 2014] and traditional development is the selection and approval of a concept for further development. In traditional development, here called Point-Based Design (PBD) [Ward et al. 1995], the selection of a single concept is made early, when the knowledge and understanding of the product is low. This single design is then re-worked and improved in an iterative way until a feasible solution is arrived at. In SBD [Ward and Sobek 2014], no single concept is selected in an early phase of development. Instead, convergence towards a solution is achieved by thoroughly investigating the design space to be able to make well-founded decisions on where to focus the continuing design work. When a concept is deemed unfeasible, it is eliminated from the set of active possible solutions, see Figure 1. A challenge with SBD is that it is not a prescriptive methodology. This implies that it needs to be adapted to each individual application.

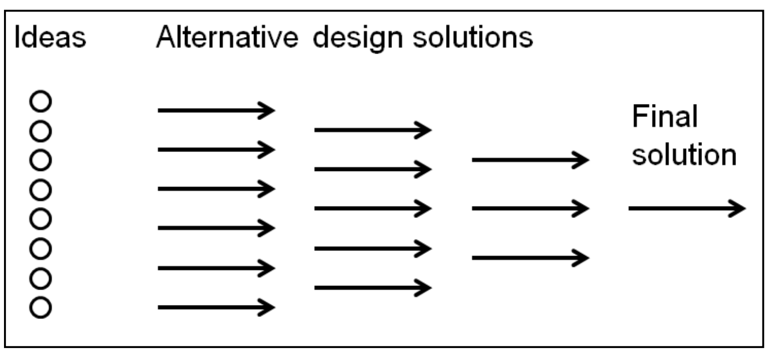

Figure 1. An SBD process, inspired by Ward et al. [1995]. Design solutions are generated from ideas. Constraints are narrowed as knowledge is gained. Inferior solutions are eliminated and the process converges on a final design

Work has been done to test and implement SBD. One example is the substantial effort of Al-Ashaab et al. [2013] to further develop and test the technique in an industrial environment. Other examples are Raudberget [2015a, 2015b]. There is however a lack of similar work on simplified methods in which SBD is combined with creative methods.

2.2 The 6-3-5 method

In design theory, Pahl et al. [2007], as part of early phases in product development, describe solution-finding methods. Two of these are intuitive: the 6-3-5 method and the gallery method [Pahl et al. 2007]. They are claimed to generate the widest possible range of ideas [Pahl et al. 2007]. In the 6-3-5 method six participants, after familiarizing themselves with the problem, each create three solution concepts and then pass them on their respective neighbour who further develops them. The process continues until the concepts have returned to their original creators and have been processed by the other five participants, hence the name 6-3-5.

2.3 Gallery method

In the gallery method [Pahl et al. 2007] a group of persons work on the same problem by describing possible solutions to it on a sheet of paper. After concepts have been created, the sheets are posted on a wall and everyone involved can view all alternatives and be inspired by each other's ideas. A second round of solution creation is then performed and the new concepts are posted. The participants view all of them and promising candidates are selected.

The concept generation phase is described by Ulrich and Eppinger [2012] as a five-step method where team knowledge and creativity is one means of generating concepts. Tools in this are analogy-making, wish and wonder, related and unrelated stimuli, setting of quantitative goals and the gallery method.

2.4 Pugh's method for controlled convergence

Pugh's method aims at controlling the design convergence [Pugh 1991, 1996]. 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 "+", same "S" or worse "-" than the datum with respect to different criteria (see Table 2). This relative comparison between individual properties of the design alternatives and the datum is an important feature of the method. It is easier for humans to compare a solution to a datum and assess whether it is better or worse than the datum than it is to assign a numerical score to it.

Table 2. An evaluation matrix (Pugh matrix) according to Pugh [1996]

	Concepts			
Criteria	1	2	3	4
A	D	+	-	+
B	A	-	+	S
C	T	S	-	+
Σ+	U	1	1	2
Σ-	M	1	2	0
ΣS		1	0	1

One approach to use Pugh's matrix in Set-Based trials was presented by The Lean PPD project [Al-Ashaab et al. 2013] which involved several industrial and academic partners throughout Europe. The authors use a Pugh matrix to select the best concept as part of the suggested methodology. A weakness of the traditional Pugh methodology is that it relies on human judgment rather than facts, and a challenge is to understand the properties of a technical system without first having designed, built or simulated it. Another weakness in a Set-based perspective is that the Pugh matrix is not suitable in its original form since it aims at selecting the best alternative. In this research we use a Set-based process with a Pugh matrix to eliminate alternatives that are not feasible based on tangible facts, which is much easier to do at a stage when knowledge about and understanding of the solutions is scarce.

3. Research approach and the collection of empirical material

The research process described in this paper followed the Design Research Methodology (DRM) for the development of design support [Blessing and Chakrabarti 2009]. The applied research approach did not follow DRM in a strict sequence from stage 1 to stage 4 though, but was performed in a non-linear fashion. The reason for this was that the ISBD methodology was not considered mature enough to be evaluated against the goals in a concluding Descriptive study 2. The process was iterated between stages

II and III until the result was satisfactory. The authors of DRM however state that the stages can be passed in a different sequence and the research process sequence is described in Table 3.

Table 3. The research process in relation to the DRM framework

	Stage	Description
I	Research Clarification	Identifying the need for ISBD in literature and formulating the research question
III	Prescriptive study	Framing the initial prototype methodology variant A
II	Descriptive study 1	Applying variant A in a "safe" environment
III	Prescriptive study	Analysing variant A and refining it into variant B
II	Descriptive study 1	Applying variant B in several cases and evaluating the results
III	Prescriptive study	Analysing variant B and refining it into the final variant C
IV	Descriptive study 2	Applying variant C in one case and evaluating the results

The Research Clarification stage was based on literature to verify that a need for the suggested support existed. 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 part of workshops with industrial collaborators aiming at understanding the ISBD methodology to the extent that it should be possible to identify which parameters are the most important for the success of it. 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 formulate a methodology that could be introduced, learned and applied in one work day. To support the research, the following research question was agreed on: How can a design team learn, apply and implement SBD on a design problem in an industrial environment in one day?

The following indicators of success were formulated:

- Does the methodology generate more ideas than the current way of working in the firm today does?
- Do experienced engineers accept the methodology as a new way of working?
- Do experienced engineers accept the results that the methodology generates?
- Can the methodology be learned in one day?
- Can a firm use the methodology without the support from researchers after that day?

3.2 Case study setup

The study was a joint venture between industry, Chalmers University of Technology and SWEREA IVF. Information was collected through five workshops, and by interviewing the participants. The setup is a multiple case study [Yin 2009] of mechanical design having tree main cases and two slightly different ones. It differs from the description of Yin [2009] in that it involved a portion of action research [Oosthuizen and Williamson 2002] where 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 in which the participants of the study did not have the sufficient background to be able to learn it on their own, i.e. without the support of the researchers.

3.3 Collection of empirical material

In Case 1, the workshop was recorded by one researcher who first introduced the ISBD methodology and then made observations and took notes. Photos were taken of the Pugh matrix, the datum design, the concepts, the explanations of the knowledge gaps and the suggested measures to bridge these gaps. Cases 2 and 3 were held in a course context and were recorded by one researcher who also acted as a teacher. Photos were taken of the results documented by the participants. In case 2 the course was assessed by using a questionnaire, which resulted in extraordinarily high marks. Cases 2 and 3 were, from a research point of view, held in a less demanding environment that was easier to control and thereby to evaluate the results from. Cases 4, 5 and 6 aimed at evaluating the ISBD methodology in a true industrial environment. Two researchers recorded cases 4 and 6. They were recorded through observations, clocking of times for each step in the workshop, photos during the workshops (see Figure 3) and of design concepts, and collection of Pugh matrices, descriptions of knowledge gaps and suggested measures to bridge the gaps. Case 5 was run by the firm without the presence of the researchers. Here, the data was collected retrospectively though oral communication after the workshop and by viewing sketches of design concepts. Table 4 summarizes the different cases.

Table 4. The collection of empirical material described in chronological order. In total 45 persons has participated in the studies (* same 11 persons)

Case no.	Participants	Number of participants	No. of groups	Vari-ant	Application type/case	Environment
1	Industrial representatives in research project	8	1	A	Industrial design	Research institute
2	Industrial representatives in course	10	3	B	LPD course	Conference facilities
3	Line managers from firm A	10	2	B	LPD course	Industrial/firm A
4	Designers from firm B	11*	2	B	Industrial design	Industrial/firm B
5	Designers from firm B	11*	2	B	Industrial design	Industrial/firm B
6	Designers from firm C	6	1	C	Industrial design	Industrial/firm C

One of the researchers was replaced between sessions so the total number of researchers having observed at least one workshop is three. Information such as time between each switch in the 6-3-5 method, number of solutions and type of knowledge gaps was recorded. Narratives in the form of sketches and Pugh matrices were also documented and photos were taken in each session. Each case was also followed up by interviewing participants about how they perceived the workshops.

4. Development of the ISBD methodology

The concept "methodology" is defined by Hubka and Eder [1996] as a “coordinated grouping of methods”, which is how the concept is used in this research. Three variants of the ISBD methodology were iteratively developed before arriving at the final version that met the stated goals of the research. The variations of the method differ in the way alternatives are generated, presented and evaluated, and how knowledge gaps are identified. In this context a knowledge gap is a piece of missing information or knowledge needed to make a key decision to be able to proceed.

The basis of the methodology is SBD and generic methods for ideation and evaluation. Sobek et al. [1999] characterize SBD as engineers and product designers “reasoning, developing and communicating about sets of solutions in parallel and relatively independently”. We were therefore looking for a way to combine solitary reflection with team collaboration. The chosen methods must also match the constraints on the time available, the number of participants, resources needed and the type of ideation that can be accomplished.

There are several procedures for ideation, and the first step was to identify methods that were suitable for the chosen size of the design team with 5-10 members. The 6-3-5 method was preferred because it allows individual work with controlled input from the other participants. The drawback is that it may not work for all types of solutions since it is, in this case, based on sketches of physical design that must be possible to embody in a hand drawing. For the evaluation method, Pugh's matrix and the method of controlled convergence were chosen since they enable decisions to be made transparently. In the final variant C, the gallery method was added as a second idea generation and assessment method to strengthen the collaborative discussion of each solution.

4.1 Adaptation of generic methods to the specific setting

In the development of the ISBD methodology it was found that the generic methods as presented in textbooks are not in their original form suited to an industrial context. The methods must therefore be adapted to the new situation. For the 6-3-5 method the standard scheme of six participants creating three solutions each during five minutes per solution is unfeasible. In all cases 20-30 minutes were used before the initial solutions were passed on to the next participant. In all cases the time for each idea generation session before passing the solutions became successively shorter as the exercise continued. The number of participants for each solution-generating loop can also be varied depending on the time available and must not be fixed to six, as the method prescribes. The 6-3-5 method also requires the participants to work independently in silence, but we found that a limited conversation between them was beneficial in order to explain to each other what they had drawn. For the number of solutions, two or three initial ideas per person seem adequate, and each solution was created on its own sheet of paper.

Convergence towards a solution is done in several steps. In variant C, the initial investigation of the design space was inspired by the gallery method, in which all solutions are posted on a wall. The difference between the gallery method as described by Pahl et al. [2007] and the one used here is that the ideation stage was carried out using the 6-3-5 method. In the version of the 6-3-5 method by Pahl et al. [2007], solutions to problems are described using keywords, whereas in ISBD, sketches on A3 sheets are used to do the same thing. In the presented setup, it encourages designers to reason about feasible regions of the design space and can be seen as an implementation of the SBCE principle 1 [Sobek et al. 1999]. The concepts were presented by the individuals who initiated them, and the other participants asked questions and provided suggestions for improvement.

The emphasis on identifying knowledge gaps is an important feature of the ISBD methodology. A first elimination of weak solutions was done by putting Post-it notes on the individual concepts (see Figure 3), with statements of the knowledge gaps needed to bridge in order to ensure successful completion of them. The remaining concepts were distributed among the participants for further refinement. Subsequent evaluation of the alternatives was carried out with an inverse Pugh matrix (see Figure 2), in which the least feasible concepts are eliminated instead of selecting the best alternative, as with standard Pugh matrices. Concepts are eliminated based on the knowledge gaps, measures to bridge them and the scores in the inverse Pugh matrices, and the remaining ones are further developed. This induces a converging design process with a repeated development/evaluation cycle as described in Raudberget et al. [2015a] and which corresponds to the SBCE principle 2. The evaluation is done in a dialogue between all participants to ensure that the maximum amount of information is available for the evaluation.

		Concepts			
		1	2	3	4
Knowledge Gaps (KG)		Description of KGs and assumed ways to bridge the KGs of concept 1	Description of KGs and assumed ways to bridge the KGs of concept 2	Description of KGs and assumed ways to bridge the KGs of concept 3	Description of KGs and assumed ways to bridge the KGs of concept 4
Criteria	A	+	-	+	D
	B	-	S	S	A
	C	S	-	+	T
	D	S	+	S	U
Σ+		1	1	2	M
Σ-		1	2	0	
ΣS		2	1	2	
Net score = (Σ+) - (Σ-)		0	-1	2	0
Eliminate			Yes		

Figure 2. An inverse Pugh matrix. Concept 2 is eliminated based on an overall assessment of net score, knowledge gaps and assumed ways to bridge them

4.2 Refining the ISBD methodology

Initially, the researchers suggested variant A, see Table 4. It was presented in case 1, in which a design problem was presented by one of the participating firms. The contributors came from different firms besides the one presenting the design problem. Each participant sketched a single solution on a paper without communicating with others. The solutions were evaluated collaboratively using an inverse Pugh matrix. Knowledge gaps in the concepts were identified, and the least feasible alternatives were eliminated. The focus of this first trial was on assessing the new inverse Pugh matrix and the method of identifying knowledge gaps. The ideation phase was therefore not the centre of attention and a need for improvement was identified with respect to the solution generation method.

Variant B was tested in two cases as part of a course in Lean product development for professional engineers. Case 2 had participants from several firms and case 3 had several participants from the same firm. Variant B differed from the first in the sense that the 6-3-5 method was added. This strengthened the ideation phase, but it became obvious that it was necessary to improve the process of convergence of the set of tentative solutions before applying the Pugh matrix. The gallery method was therefore introduced in variant C. It was tested in an industrial context on genuine design problems in two cases in two firms.

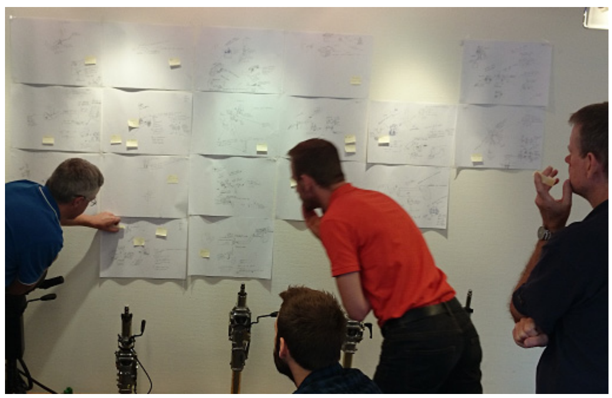

Figure 3. Design solutions are posted and designers try to identify inferior solutions to eliminate

4.3 Applications

The industrial applications used are as follows: Case 1 is a small staircase to be fitted on the battery box of a heavy truck, case 4 and 5 are locks for doors and case 6 is a tilting and locking mechanism for steering columns in off-road vehicles.

5. Description of the ISBD methodology

After going through three successive iterations, the ISBD methodology is based on the steps in Table 5.

Table 5. The steps of ISBD

Step	Description
1	A brief introduction to SBD, the 6-3-5 method, the gallery method and the inverse Pugh matrix. The workshop leader gives a short lecture on these subjects.
2	Presentation of the design problem. All participants should be well informed of the problem at hand in order to be able to contribute to its solution. Previous designs, physical artefacts, lists of requirements, descriptions of targeted users etc. can be used.
3	Solution generation by the 6-3-5 method. The workshop participants are typically seated around a table and equipped with A3 sheets, pens and the description of the design problem.
4	Presentation of the concepts by posting them on a wall, start of the gallery method. An example of this can be seen in Figure 3.
5	Elimination of solutions by identifying problems with them. Issues were written on Post-it notes (see Figure 3) and solutions with several problems were removed and stored in the design repository.

6	Assigning of the remaining sketches to specific participants for further development. The participants are typically seated around the table again and sketching on improved solutions based on ideas received from the discussions in front of the wall in steps 4 and 5.
7	Posting of the improved solutions and use of the inverse Pugh matrix. Each concept is compared with the datum.
8	Identification of knowledge gaps and ways to bridge them, as evaluation criteria. For each concept in the Pugh matrix knowledge gaps are identified and tentative measures to bridge them are described. This can be testing, building prototypes, searching for information, consulting experts etc.
9	Elimination of the least feasible solutions based on the results from the Pugh matrix, knowledge gaps and measures to bridge them.

A comparison of the features of the ISBD methodology, SBD and traditional PBD is given in Table 6. Inputs to the comparison are the results from the described study in section 4, resulting in the definition of ISBD in section 5 and inputs from Ward et al. [1995] and Sobek et al. [1999].

Table 6. Comparison between ISBD, Set-Based Design (SBD) and Point-Based Design (PBD)

Feature	ISBD	SBD	PBD
Starts with multiple design solutions	Y	Y	Y
Has an integrated creative method to generate multiple solutions	Y	N	N
Simultaneously explores the feasibility of multiple design solutions	Y	Y	N
Selects the most promising design solution	N	N	Y
Continuously eliminates inferior solutions	Y	Y	N
Fixed specification describing the requirements of the design	Y	N	Y
Design specification based on intervals	N	Y	N
Iterations to correct failures as a typical means	N	N	Y
Convergence is built into the method to reduce sets of designs and arrive at a final solution	Y	Y	N
Early detection of knowledge gaps of design solutions	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 of sets of solutions	Y	Y	N
The process can continue as a true SBD process	Y	Y	N

The method somewhat corresponds to the phase Concept Development in the product development process of Ulrich and Eppinger [2012].

6. Discussion

The research question was: How can a design team learn, apply and implement SBD on a design problem in an industrial environment in one day?
Answer: This can be done by using the ISBD methodology as described in this paper.

6.1 Fulfilment of success factors

The result is compared with the success factors in Table 7.

Table 7. Evaluation according to the success factors

Success factor	Result
Does the methodology generate more ideas than the current way of working in the firm today does?	Yes, expressed by experienced engineers at the participating firms
Do experienced engineers accept the methodology as a new way of working?	Yes, none of the participants disapproved, rather the opposite
Do experienced engineers accept the results that the methodology generates?	Yes, none of the 45 participants disagreed
Can the methodology be learned in a day?	Yes, all cases were completed within eight hours
Can a firm use the methodology without the support from researchers after that day?	Yes, this was done in one case

6.2 Limitations

The developed methodology is a simplified version of SBD. The short time available makes it impossible to perform experiments to learn about the different concepts. Time is too short also to do a second iteration on the selected solutions on the same day. The process can however probably continue as a full version of SBD once the firm has learned to use the simplified version. We only use the first two principles of SBCE [Sobek et al. 1999].

6.3 Reliability of the results

The observations were conducted by three researchers. The methodology had a high acceptance among the participants. These were experienced engineers indicating that the methodology is useful in their context. In total, 45 experienced design engineers tested the method at different maturity levels on six 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 thought it was interesting, useful and inspiring and there was no doubt that the methodology could be used in the intended time.

6.4 Generality of the results

The method was tested on three different industrial mechanical design cases in three different firms. In cases 4, 5 and 6, where the method had reached a high maturity level, the test persons were experienced designers in mechanical design at a comparable level of skill. One of the firms involved in case 5 has continued to use the method themselves after the introduction, with success. The results of the described work were presented to a reference group of 14 persons (in a lean product development interest group) from eight different firms, and the impression of the group was that the method is worth trying. This strengthens the conclusion that ISBD works well in the domain where it has been tested and applied.
The method has not been used in cases involving other disciplines than mechanical design.

7. Conclusions

From the above described results we conclude the following:

- ISBD is a feasible methodology for mechanical design problems
- ISBD is feasible for introducing parts of SBD
- ISBD can be introduced, applied and implemented in one day

7.1 Future work

Future work could be to

- develop a follow-up workshop after day one to investigate how the SBD process progresses and to measure the long term effects

- introduce systematic methods for concept generation, such as morphological matrices. This would mean the introduction of an additional means to generate design solutions. The impact of this on the number of designs solutions and their feasibility could be interesting to study
- test the ISBD methodology on problems in other areas than mechanical design, such as e.g. design of services, electronics and software. The latter is particularly interesting since it probably could include testing of solutions for pieces of software that is possible to write in one or two hours
- carry out longitudinal studies of existing cases

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