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ENGINEERING DESIGN PROBLEM IN A CO-EVOLUTIONARY MODEL OF THE DESIGN PROCESS

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1. Introduction

The engineering design process can be considered as the transformation of expressed needs into a complete product definition. Besides the expressed needs, designers have to take into account constraints. In this sense, the design process can be seen as a problem solving process, whose problem has some properties that will be explained.
Several models of the design process exist. We will question how the design problem is addressed in the classical approaches, and so identify the relevance of co-evolutionary approach to describe the design process. A co-evolutionary model, based upon two domains and four activities is then proposed. A well-established design corpus has been eventually used to validate its relevance to describe a real design process. This relevance promises to use this model as a basis to support the design process.

2. The design problem

The design process can be seen as a problem solving process. Indeed, its achievement corresponds to the shift from a problematic situation, in which needs considered are not satisfied, to an objective situation in which they are. Considering a design context, the problem has some particular properties. This problem is open-ended, as its solving does not consist in finding the only solution, but in finding a satisfactory one (or several ones). In this sense, the number of satisfactory solutions, if anyone exists, cannot be known initially. The solutions proposed to a design problem are not true or false, but more or less acceptable. Design problems are considered ill defined, because designers have, initially, only an incomplete and imprecise mental representation of the design goals or specifications [Simon 1981]. Eventually, the design problem is something complex. Indeed, when judging an acceptable solution, this judgment implicates several different, non-comparable and non-independent aspects. The work presented in this paper deals with the design process in a modern industrial context. This situation goes together with the implication of several stakeholders in the design process. The topic treated here concerns on one hand the problem expression in such a context, and on the other hand the evaluation needed to judge whether or not solutions proposed are satisfactory.

2.1 The design problem in the systematic approach

One of the most well established model of the design process is the systematic approach [Pahl & Beitz 1996]. It considers the design process as a set of successive stages that correspond to the achievement of associated tasks by concerned stakeholders. The first stage, called *product planning and clarification of the task,* consists in analysing, expressing and decomposing the design problem. The following stages then deal with the solution definition. These stages aim at solving the problem expressed according to a generic progression, from the most global and abstract aspects to the most detailed and physical or concrete ones.

2.2 The design problem in concurrent engineering

During the last years, the increasing complexity of product, market competition and pressures on quality, cost and lead-time have resulted in an evolution of the industrial organisation. The design tasks that were led successively are now treated in parallel [Solhenius 1992]. Consequently the relation between the different design stakeholders, which was previously a one-way contractual prescription, is nowadays a cooperative and interactive net. This evolution is taken into account, among other works, by those that describe, besides the parallelism of tasks, the parallelism of several domains, spaces or worlds, which relate to the different possible points of view, with different abstraction levels, on the solution designed [Suh 1990, Mortensen & al. 1999].

2.3 Limits of these approaches

The two approaches briefly presented above fail, in our sense, in taking into account all the design process characteristics. Indeed, the systematic approach presupposes that the design problem can be initially known, expressed and decomposed into independent sub-problems, which will be resolved during the achievement of independent successive stages. The unavoidable iterations, which occurred during real design processes, are a proof of the non-relevance of this assumption. Moreover, the initial problem expression tends to limit the solutions space to those that fit the chosen decomposition. Those two points are incompatible with on one hand the design problem properties mentioned above, and on the other hand with some cognitive aspects of the design activity. Indeed, works in cognitive psychology tend to prove that designers, rather than following a top-down and a priori planning and problem decomposition, plan their tasks according to opportunistic iterations [Bonnardel & al. 1996]. The domain-based approaches offer an alternative to the classical sequential approach, by decorrelating the points of view dimension and the detail dimension. Nevertheless, according to the authors, they are still in discordance with cognitive aspects. Existing models are indeed considering the different domains or worlds taken into consideration as successive points of view on the product, while cognitive science revealed the simultaneity of these different ones [Darses 1997].

3. The co-evolutionary approach

3.1 Existing background

Domain-based approaches mention the coexistence of different domains or spaces, corresponding to different points of view on the product designed, within the design process. Those domains are progressively defined and detailed throughout the design process. Other approaches, based on a similar basis, consider the coexistence of two domains, the one of problem expression and the one of solution definition. Thus, according to Simon [Simon 1981], the design process is composed of problem solving activities, i.e. proposals and definitions of solutions according to the problem expressed, but these activities intrinsically alternate with problem setting and framing ones, in regard to the solution defined.

Maher [Maher & al. 1996] proposes a so-called co-evolutionary model, which describes the design process as parallel evolutions of both problem-space and solution-space dimensions, which are linked by focus and fitness activities. Brissaud [Brissaud & al. 2003] adopts a model based on the same spaces, but in which the shifts between the two spaces are associated with alternative conjectures proposals and criteria emergences.

3.2 Interest

These models, seen as representation modes of the design process, totally decorrelate the activities led, the planning and the points of view adopted dimensions. In this sense, they offer an opportunity to situate design activities according to the domains concerned rather than to an a priori schedule. Thus it correlates the opportunistic aspect of decomposition and planning, together with the noticed

simultaneity of the points of view naturally adopted by design stakeholders. Moreover, by explicitly treating an evolutionary problem expression, it fits totally the openness and ill-definition properties of the design problem.
Considering the objective of this paper, the co-evolutionary models offer a basis to investigate for the support of problem expression seen as a dynamic aspect of the design process. Indeed, this problem expression can evolve during the whole design process, according both to intrinsic shifts between two successive problem expression states and to interactions with the solution definition state.

3.3 The co-evolutionary model in a concurrent engineering context

We have mentioned the nowadays increasing implication of several different stakeholders in the design process. This goes together with an increasing complexity of the aspects that have to be taken into account, the different stakeholders being representative for the whole product life cycle, from cradle to grave. While many works aim at integrating stakeholders, their objectives and skills in the solution definition process, the problem expression in such context is quite evaded in literature. The approach presented in this paper aims at highlighting the importance of this issue. In this sense, the problem expression, and the solution definition are considered in this paper as shared and common within the design team. We so assert here the relevance of the co-evolutionary model to integrate stakeholders by a shared, common and evolutionary problem expression.

4. An activity-based co-evolutionary model of the design process

From the generic models described above, we have been developing a co-evolutionary model that aims at offering a basis to problem expression support, in a concurrent engineering context. To carry out such a task, it is advisable to detail the existing representations. In our sense this detailing work has to focus first on the collective aspect of concurrent engineering, then on the activities whose implementation refers to the problem expression.
According to the chosen basis for our approach, it is possible to define generic activities. Indeed the model adopted describes the design process as the co-evolution of two domains. Considering an activity as an elementary process that allows shifting from a situation to another where either the solution definition or the problem expression (or the shared knowledge about them) has changed, the adopted representation (Figure 1) allows to distinguish four activities (Table 1).

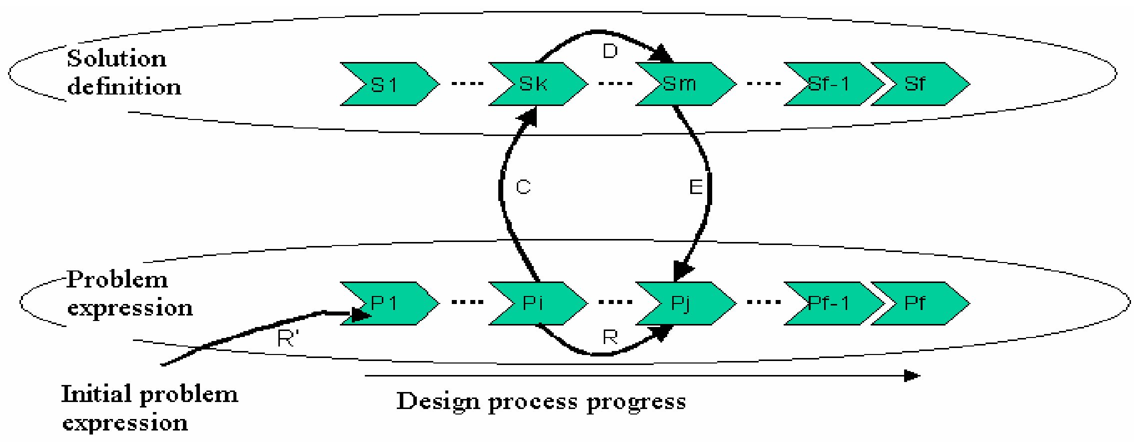

Figure 1. The proposed model of the design process including design activities

Those four activities are supposed to occur all along the design process, alternatively but apart from any pre-established scheme. We retrieve the classical triplet {specify generate evaluate}. Nevertheless the chosen representation led to distinguish, inside the previously called "generate" activity, between the conjecture and the definition. Indeed, in our sense and due to the collective context considered, the conjecture activity refers to the individual, imaginative and creative act that results in a new idea, while the definition activity denotes the communication acts that then occur within the team.

Table 1. The four design activities

Conjecture (C)	This activity is the one led by a design stakeholder proposing a new solution, or a new element to an already considered solution, supposed to solve the problem expressed.
Definition (D)	This activity is the one consisting in defining, setting, explaining and communicating a proposed solution (or proposed elements of a solution) among design stakeholders.
Evaluation (E)	This activity is the one consisting in judging a proposed solution in regard to the problem expressed.
Reformulation (R)	This activity consists in setting a new problem expression, or modifying the one existing. The first initial problem expression is considered as a particular reformulation.

5. Validation

5.1 The design corpus

In order to question the relevance of the followed approach, the proposed model was confronted to an existing well-established design corpus. The design corpus used results from the Delft Design Protocol [Cross & al. 1997], and is referenced as DPW94.1.14.5. This issue implicated a team of three designers of various skills, who were asked to produce, after a limited length of time, the set of documents and annotated sketches that describe a chosen solution concept to a given assignment. It consisted in defining a carrying/fastening device that aims at carrying a given backpack on mountain bikes, focusing on some particular aspects such as ease of use and price. The corpus is composed of an audio/video recording of the whole process (with four simultaneous framings), together with a written transcription of the dialogues and pictures of intermediate objects produced.

5.2 Instantiation of the activity model

The written transcription was the only part of the design corpus to be used here. It consists in a spreadsheet containing, on each row, a time moment and length indication, the name of the designer speaking, and the content of his speech (and the possible remarks of the researcher who supervised the experiment). This transcription has been captured according to the activity-based model proposed above, i.e. by associating one of the four generic activities to each statement. You can notice that conjecture activities haven't been considered alone, but only with definition activities (C-D). Indeed, our recording being based on communicated statements, each conjecture, i.e. idea, solution proposal has intrinsically been associated with a definition, communicative activity. Table 2 illustrates this instantiation for two extracts of the design corpus, the first one during the first part of the time schedule, the second almost at the end of the design process. The five columns of Table 2 contain respectively the moment when the statement was pronounced; its author initial (I, J or K); the statement itself; the activity identified (E, R, C-D or D) and a personal interpretation.

5.3 Results

The performed capture revealed, in our sense, two aspects that validate our approach.
First, when recording the corpus, the authors have noticed the ability of the four activities proposed to describe most of the statements communicated between the design team members, and this without ambiguity when identifying the concerned activity. The opinion raised in this paper is that the co-evolutive model, by situating design activities in regard to the domains they are concerned with, insures this completeness and avoids ambiguity.
Secondly, the recording of the whole corpus with the method described above results in a validation and reinforcement of the hypothesis adopted here. Indeed, it shows the design process as the macroscopic resolution of an open-ended and ill-defined problem, according to an unforeseeable planning progress. Figure 2 illustrates this vision, by showing that the four types of activity are led, and consequently that both problem and solution spaces are addressed throughout the whole design process.

Table 2. Two extracts from the corpus DPW94.1.14.5 in terms of activities

<table>
<tr><th colspan="5">First extract</th></tr>
<tr><td>00:45:55</td><td>J</td><td>um one of the things I was thinking that if you did this one</td><td rowspan="2">R</td><td rowspan="2">J identifies, according to the solution considered at this moment, a new problem element ...</td></tr>
<tr><td>00:45:58</td><td>J</td><td>of the things that could be neat is people were talking about like centre of gravity</td></tr>
<tr><td>00:46:00</td><td>J</td><td>and I think that it'll be</td><td rowspan="4">R</td><td rowspan="4">…that is precised.</td></tr>
<tr><td>00:46:03</td><td>J</td><td>different for different people what their preference is a little bit</td></tr>
<tr><td>00:46:04</td><td>K</td><td>mm mm</td></tr>
<tr><td>00:46:05</td><td>J</td><td>like where they want that mass</td></tr>
<tr><td>00:46:14</td><td>J</td><td>maybe the if there's a thing that comes down to here you could have it so that it adjusts so you could kinda lever the pack up or down a little bit y'know if it's not a a fixed</td><td>C-D</td><td>…and answered through a new solution</td></tr>
<tr><td>00:46:21</td><td>K</td><td>seems like lower is better regardless as you say like we design in the low position and not necessarily try and get</td><td>R</td><td>a problem element is questionned</td></tr>
<tr><td>00:46:21</td><td>I</td><td>you're gonna have um</td><td rowspan="3">R</td><td rowspan="3">another problem element is set-up</td></tr>
<tr><td>00:46:22</td><td>K</td><td>the adjustability</td></tr>
<tr><td>00:46:25</td><td>I</td><td>is there gonna be an issue of the height of this I mean</td></tr>
<tr><td>00:46:28</td><td>J</td><td>what about clipping under the bottom of the seat</td><td rowspan="2">C-D</td><td rowspan="2">New solutions are proposed</td></tr>
<tr><td>00:46:30</td><td>I</td><td>yeah or even the the seat post neck</td></tr>
<tr><td>00:46:32</td><td>J</td><td>oh these things yeah</td><td>E</td><td>And evaluated</td></tr>
<tr><td>00:46:39</td><td>K</td><td>the other thing we ought to be concerned about ergonomically is that when you're at the bottom of your stroke your leg is is right in here you want to make sure you don't get too close to the seat</td><td>R</td><td>K identifies a new problem element</td></tr>
<tr><th colspan="5">Second extract</th></tr>
<tr><td>01:48:16</td><td>J</td><td>why why do we need any screws?</td><td rowspan="2">R</td><td rowspan="2">I & J question the need to have screws</td></tr>
<tr><td>01:48:19</td><td>I</td><td>er for these things that attach to here</td></tr>
<tr><td>01:48:20</td><td>J</td><td>mm mm</td><td>?</td><td></td></tr>
<tr><td>01:48:21</td><td>K</td><td>what are those called again those rear things?</td><td rowspan="2">D</td><td rowspan="2">K & I describe the considered solution</td></tr>
<tr><td>01:48:24</td><td>I</td><td>stays topstays</td></tr>
<tr><td>01:48:29</td><td>J</td><td>ugh I don't like screws</td><td>E</td><td>J judges negatively the solution with screws</td></tr>
<tr><td>01:48:32</td><td>I</td><td>I know because you'll need foot plugs too</td><td>R</td><td>I establish a problem element (that justifies past evaluation)</td></tr>
<tr><td>01:48:39</td><td>J</td><td>no we could we could wing that into the plastic you get little wing nuts that go into em insert into the plastic</td><td>C-D</td><td>J proposes and defines a new solution w/o screws</td></tr>
<tr><td>01:48:39</td><td>K</td><td>y'don't need to remove those</td><td>R</td><td rowspan="2">K raises a not real problem and so evaluates negatively J's solution that aims at solving it.</td></tr>
<tr><td>01:48:41</td><td>K</td><td>they're a part we don't ever need to once those are installed we never</td><td>E</td></tr>
<tr><td>01:48:43</td><td>K</td><td>we could insert mould them</td><td>C-D</td><td rowspan="6">The team defines a new aspect of the solution…</td></tr>
<tr><td>01:48:45</td><td>I</td><td>well there you go</td><td>?</td></tr>
<tr><td>01:48:46</td><td>J</td><td>insert mould what?</td><td rowspan="4">D</td></tr>
<tr><td>01:48:48</td><td>K</td><td>insert mould these into the</td></tr>
<tr><td>01:48:49</td><td>J</td><td>yeah OK we'll insert mould them</td></tr>
<tr><td>01:48:50</td><td>I</td><td>insert mould</td></tr>
<tr><td>01:48:51</td><td>J</td><td>cheaper (laugh)</td><td rowspan="5">E</td><td rowspan="5">…that is evaluated positively according to cost together with the problem element expressed just before (no screws)…</td></tr>
<tr><td>01:48:52</td><td>K</td><td>so that</td></tr>
<tr><td>01:48:54</td><td>I</td><td>that gets rid of four screws</td></tr>
<tr><td>01:48:55</td><td>I</td><td>no screws</td></tr>
<tr><td>01:48:56</td><td>J</td><td>no screws</td></tr>
<tr><td>01:49:00</td><td>I</td><td>but see that was where our adjustability came from</td><td rowspan="5">R</td><td rowspan="5">…and that is eventually eliminated…</td></tr>
<tr><td>01:49:01</td><td>I</td><td>in the different frame size</td></tr>
<tr><td>01:49:02</td><td>I</td><td>so now the height's gonna be</td></tr>
<tr><td>01:49:02</td><td>K</td><td>that's true</td></tr>
<tr><td>01:49:05</td><td>J</td><td>no then we need it you're right you're right you're right</td></tr>
<tr><td>01:49:06</td><td>K</td><td>put the screws back</td><td>C-D</td><td rowspan="2">…to come back to past solution</td></tr>
<tr><td>01:49:07</td><td>I</td><td>where were they?</td><td>D</td></tr>
</table>

6. Conclusion and future work

The main objective of our research is to provide a support to problem expression in a concurrent and integrated design context. The work presented above has offered to question the importance of the design process model adopted to fit with both design problem characteristics and with cognitive and human aspects. This issue was answered by the adoption of an activity-based co-evolutionary model. A well-established design corpus then validated the ability of this approach to fit a real design process. Leaning on these work and results, another part of the author's research aims at treating the support aspect of the chosen issue. In this sense, the activity-based co-evolutionary model is used as a basis to identify both the objects implicated in the activities implementation and the existing tools that aim at supporting problem expression-related activities (so called reformulations and evolutions). Thus, the co-evolutionary model offers a global point of view on the design process and its possible support, including activities, objects and tools. This allows to investigate for the implementation of such tools in respect to the design process dynamics, its cognitive aspects and the design problem characteristics.

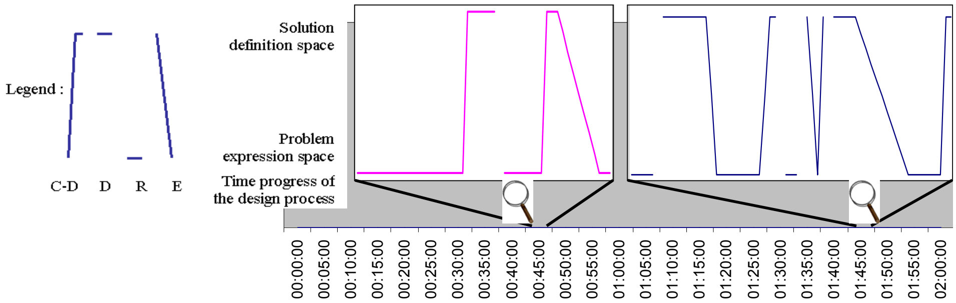

Figure 2. The activities occuring during the two extracts

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