DESIGN TO KNOWLEDGE – A ROOT DESIGN PRINCIPLE

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ABSTRACT

“Design to” and “design for” principles are used to support and improve engineering processes with regards to a specific target area. This paper introduces design to knowledge as an operationalization approach for the knowledge oriented engineering paradigm. Special focus is put on the method of knowledge stream analysis. This method is exemplarily applied on the VDI 2221 guideline as a means to identify knowledge oriented gaps along the design process, possible value losses and improvement potentials. Finally, it will be argued that, through a consistent application of design to knowledge, design processes could be improved in a way that other design to and design for principles are inherently facilitated, or even automatically fulfilled.

Index Terms – Knowledge Oriented Engineering, Design to Knowledge, Knowledge Stream Analysis

1. INTRODUCTION

Design processes are described and ordered by design methodologies, which provide frameworks of methods and tools along the progress of product creation. Significant sub-methods are provided by so-called “design for x” or “design to x” principles, design for assembly and design to cost being just two well-established examples.

This paper will elaborate on design to knowledge as a less popular, however important principle and explain its operationalization on the basis of the knowledge stream analysis method. It will be argued that this principle can be seen as a root principle, which, being taken into account, could have significant impact all over the design process and thereby also on the fulfillment of other, from this point of view subordinated, design principles.

This article is set up as follows. First, chapter 2 will set the frame for design to knowledge in the midst of the variety of design to and design for principles. Then, chapter 3 will elaborate on the role of knowledge within the design process and discuss related works in this area. Chapter 4 will give an in-depth introduction to design to knowledge with special focus on the knowledge stream analysis as one core method. Finally, the results will be discussed and conclusions drawn.

2. DESIGN TO AND FOR X

“Design to” and “design for” as terms used for design principles are not consistently distinguished between, sometimes even understood as more or less synonyms (e.g. [1]). For this paper however, “design to” will be applied for general targets or focal aspects of the design process (e.g., cost or quality), whereas “design for” will be used for (side) effects or follow-up processes to be suited by the design process (e.g., assembly or recycling). The former may therefore be of a more general character and influence a wider range of design process steps through primarily proactive measures, whereas the latter delivers more specific guidelines, often applied reactively and over a limited range of process steps around the embodiment design phase.

[1] states that design to function in the sense of the fulfillment of desired product functions generally constitutes the primary design principle, compared to which all others form secondary principles. [2] describes a multitude of design principles, mainly in the understanding of guidelines to be taken into account during detail design. One challenge in this respect is how to deal with the resulting multitude of rules and guidelines, which may potentially even be contradictory [3]. One approach would be to put several such secondary guidelines in a sequential order, which, after the basic design to function fulfillment, will be considered and traded off in iterative process steps.

However, according to the philosophy of knowledge honoring as promoted by, e. g., lean product development, see chapter 3.2.4, this paper will position design to knowledge not secondary, but aside to design to function as a second primary design principle.

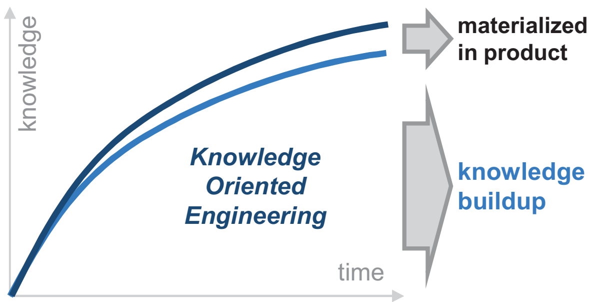

Figure 1:
Product vs. knowledge as design result

3. KNOWLEDGE WITHIN THE DESIGN PROCESS

Traditional design methodologies generally focus on delivering products within defined time, quality and cost limits. Design process steps such as described in [4] lead to this goal by identifying, concretizing and finally realizing the best-as-possible solution principle.
Knowledge within these methodologies is however not assigned a prominent role.

3.1. Role of knowledge in design methodologies

According to the analysis described in [5], knowledge is seen in traditional design methodologies as – if at all – something helpful to be applied in decision making process steps, e.g. by using supportive knowledge-based-engineering tools. It is not seen as something to be systematically built up during the design process, not as a deliverable as such.

This can be seen on the example of the design guideline VDI 2221 [4] of the German Engineers' Association. This standard provides a process flow beginning with a development task set out by product planning and ending with product documentation ready for further realization. It is thereby laid out to fulfill one predominant goal: getting a product idea realized.

Looking in detail inside VDI 2221 and its subsidiary guidelines 2222 and 2223, knowledge is explicitly mentioned twice – first in the sense of supporting the search for solution principles by using solution catalogues (step 3), and second in the sense of the provision of design rules in the context of the embodiment design phase (step 5). Creation of such rules or catalogues is to be covered by a separate process not part of the design process itself. Thus knowledge seems to be understood just in a sense of (implicit) knowledge provision and usage, not in the sense of (formalized) knowledge creation and reuse. Similar findings apply to other contemporary methodologies, such as [3, 6, 7, 8].

In contrast to this traditional understanding, the upcoming lean product development paradigm puts knowledge into the center of the design process, thereby requesting adaptations also to the traditional design methodologies and frameworks. [5] refers to this concept as knowledge oriented engineering, and proposes to raise it to an underlying paradigm for the whole design process.

3.2. Related works

Although knowledge does not seem to play a prominent role in traditional design methodologies, it is a topic researched and discussed within a variety of product development related methods, some of which will be described in the following in order to delimit them from the approach presented in this paper.

3.2.1. Knowledge based engineering

Knowledge based engineering is a term quite popular. It is used mainly to describe limited efforts of design automation based on captured explicit knowledge (e. g. [9]). It thereby makes knowledge applicable, but it does neither focus on the capturing of knowledge nor, in the sense of this paper, on making it a design target. It has thereby to be distinguished from broader concepts such as knowledge oriented engineering [5], which is the basis for design to knowledge as promoted in this paper.

3.2.2. Knowledge auditing

Knowledge auditing is a method of knowledge management, which focuses on analyzing inventories, holders and flows of knowledge within processes (e. g. [10, 11]). It can thereby provide a foundation for follow-up knowledge management programs and also be helpful as a basis for the design to knowledge proceeding described in chapter 4 of this paper.

3.2.3. Value stream analysis

Value stream analysis is a concept originating in the lean production concept. A multiplicity of related methods is described (e.g. [12]). The basic idea is to analyze (production) processes with special focus on the (product) value potentially added by each process step, and on eliminating steps which do not contribute to this value and are therefore to be considered waste. Some of these methods include knowledge in their understanding of value (e.g. [13]). Transferring this idea to product development, where both value and waste can be concretized in the form of knowledge creation or loss [5], leads to the idea of knowledge stream analysis as described in chapter 4.

3.2.4. Lean product development

Lean product development is a philosophy originally erected on Japanese product development practices. Its core idea is a transfer of lean production ideas to product development, leading to a special honoring of knowledge along the design process. It thereby sets the philosophic ground for the knowledge oriented engineering paradigm [5] and the design to knowledge approach presented in this paper.

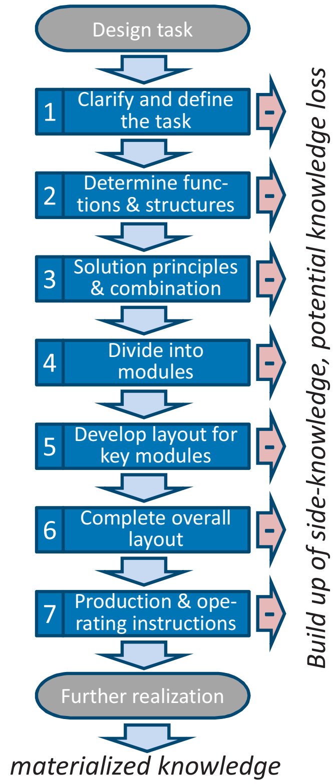

Figure 2:
Knowledge stream analysis (base process: [4])

4. DESIGN TO KNOWLEDGE

Design to knowledge forms the operationalization of the knowledge oriented engineering paradigm. According to the “design to” understanding above, it means seeing knowledge as a target and focal aspect of the design process, thereby setting it as a second design deliverable aside to the generally focused-on products. According to figure 1, a significant ratio of knowledge generated throughout the design process may be wasted if the focus would be put on the product outcome, only.

4.1. Concept

Applying design to knowledge requires two main steps. First, the knowledge stream throughout the design process has to be identified. To achieve this, each process step has to be analyzed regarding the entirety of its inputs and outputs, see figure 2. If, e.g., one solution principle is selected for further detailing, all discarded solutions with all their pros and cons form valuable knowledge potentially lost, if not explicitly honored as such. In the following, this proceeding will be referred to as *knowledge stream analysis* as its underlying understanding is similar to that of value stream analyses, but has to be distinguished from that of knowledge flow analyses, as described in chapter 3.2.

Second, concepts have to be developed in order to make use of this knowledge, if applicable. E.g., methods or tools could be established to capture the side knowledge and make it available for further reference in future design projects.

Generally, this approach is meant to be applied as a process analysis and synthesis tool in order to improve real design processes. However, it can also deliver valuable conclusions when applied on theoretical process models. Thus, in this article, both steps will be described on the example of the VDI 2221 process.

4.2. Knowledge stream analysis

In the following, the knowledge stream along the design process chain of VDI 2221 is described using flow diagrams as depicted in figure 3.

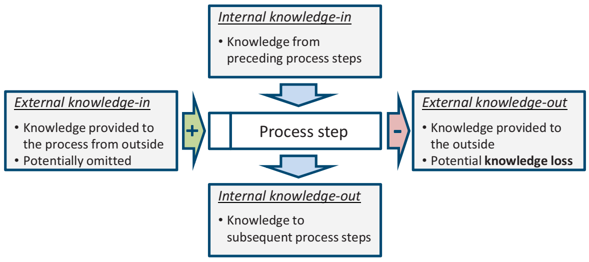

Figure 3:
Knowledge stream analysis block for general process step

The vertical knowledge stream represents the knowledge transferred along the design process, which finally leads to the materialized product, compare figure 2. Thus, the knowledge-in of one process step equals the knowledge-out of its predecessor step, provided that no knowledge gets lost or is misinterpreted during this transfer. The horizontal knowledge stream represents knowledge, which is either fed into the process from the outside (left) or flows out of the process (right). Both sides of this stream are to a certain extent optional, i. e. these streams can be omitted in the sense of neglected input on the in-side, or knowledge loss on the out-side.

4.2.1. Pre-stage of the design process

The design process of VDI 2221 starts with the reception of the design task or problem, which is provided by product planning. Product planning is an activity not covered by the guideline as such, but described in the adjacent VDI 2220. Its main role is to provide a product development order based on customer and/or strategic input.

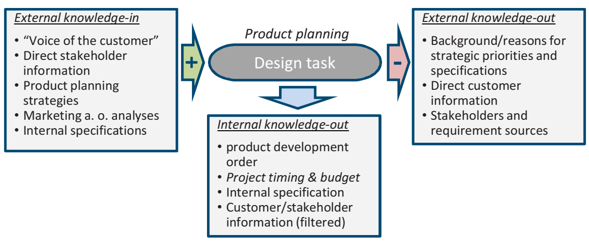

Figure 4: Product planning as input provider to the design process

Looking at the knowledge stream as depicted in figure 4, the main risks for knowledge loss in this step result from product planning's filtering position in between the customer and other stakeholders on the one side, and the design department as the design process owner on the other side.

4.2.2. Step 1: Task clarification

Once received from product planning, its design's task to interpret and complete the product development order and to generate an internal, potentially prioritized requirements list which will then accompany the complete design process. Also, potential knowledge gaps identified will be initiated to be addressed by the follow-up process.

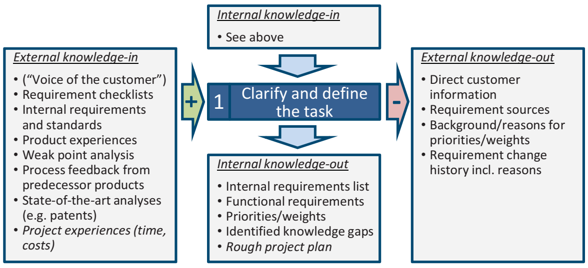

Figure 5:
Knowledge streams through process step 1

A side activity started with this process step is project planning, which is not explicitly covered by VDI 2221.

The knowledge streams depicted in figure 5 show that the information received from product planning is generally not sufficient to fulfill these tasks, as it may not be complete, especially regarding internal information, or filtered regarding customer, stakeholder, or strategic information. Furthermore, in this step explicit or implicit knowledge from experience as well as from various analyses is added to the process. The main risk for knowledge loss in this step lies in the reasoning behind the documentation created and its change history.

4.2.3. Step 2: Functional design

The following functional design phase abstracts the requirements provided and tries to identify solution models on this level. This step is often omitted (also according to other methodologies, e.g. [7]) or seen as difficult; external knowledge from catalogues or predecessor products may therefore support this work. Result of this step is an (ideally) all-embracing, thought-through functional model of the envisioned design.

As functional design builds the first synthesis step in the process, knowledge about the discard of ideas (with reasons) and implicit understandings may leave the process in this step, see figure 6. It will then be kept – if at all – as implicit knowledge in some designers' minds.

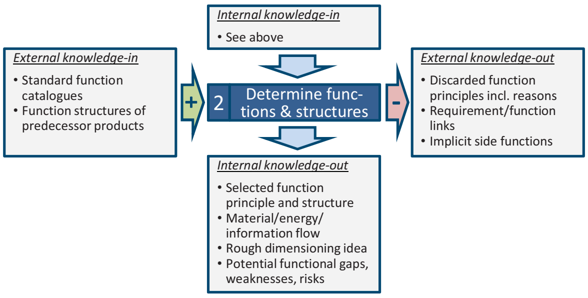

Figure 6:
Knowledge streams through process step 2

4.2.4. Step 3: Selection of solution principles

After having understood the functional concept of the design, this is the most prominent step on the way to defining the best-as-possible solution. Its success heavily depends on embracing external knowledge and successfully applying creativity covering a wide search area, see figure 7.

According to VDI 2221, aspired result of this step is the decision upon main and sub solution principles to be further detailed in follow up steps. This proceeding is however questioned by lean product development approaches [5].

Based on this step, the project plan can be further detailed and transferred in a project controlling mode.

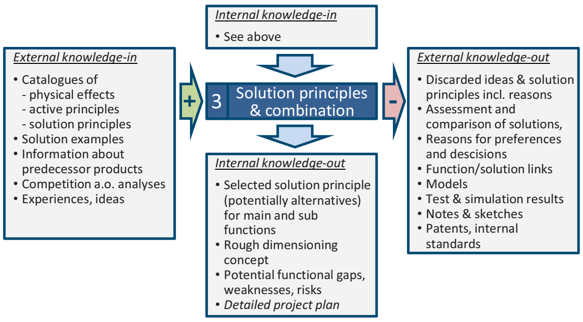

Figure 7:
Knowledge streams through process step 3

With the highly creative, but also deciding character of this process step, there is also a high amount of knowledge leaving the process at this stage. Many ideas get evaluated and discarded, tests are done, requirements are traded off and sketches discussed. If not intentionally and systematically kept, this may lead to a huge knowledge loss for the design department.

4.2.5. Step 4: Modularization

Step 4 of VDI 2221 leads the creative solution finding towards the detailing and realization phases. Its target is a product breakdown into modules to be realized company-internally or -externally.
Looking at the knowledge stream as depicted in figure 8, the realization process steps depend on external knowledge from standards, experiences and

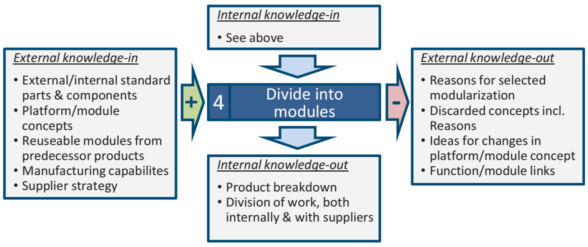

Figure 8:
Knowledge streams through process step 4

process insights. Again, knowledge loss may result from decision-related discards or process-external improvement ideas not followed up on.

Furthermore, for all process steps from 2 to 4, the relationships and links between the respective focus objects, i. e. requirements, functions, solutions and realization modules, may not be explicitly and consistently captured.

4.2.6. Steps 5-7: Detailing

The final three steps of the process are determined to detail, document and finalize the design for further realization. Thus, like in the previous steps, external knowledge from standards and experiences has to be considered, see figure 9. The final documentation ends the VDI 2221 design process.

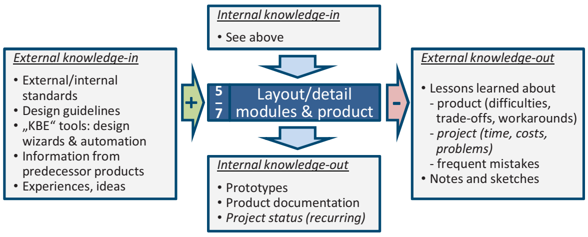

Figure 9:
Knowledge streams through process steps 5-7

The main danger for knowledge loss in this stage results from lessons learned but not lastingly documented (e. g. notes or sketches), which may be of significant extent. This information may be product or project related and of great help for follow up projects, if adequately captured.

4.2.7. Follow-up-steps of the design process

The VDI 2221 process opens into a "further realization" phase not further specified. Other design methodologies such as [7, 8] also include prototype testing or production ramp up as follow-up phases.

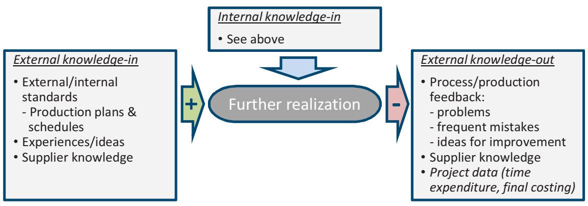

Figure 10:
Knowledge streams during further realization

With the project leaving the responsibility area of design, potentially even being handed over to suppliers, this process step is especially critical regarding the fluency of knowledge – only the minimum of documentation directly required may be transferred.

As the knowledge streams in figure 10 show, external knowledge loss may occur through not existing or not effective feedback loops back to the design area, e. g. lessons learned regarding manufacturing or project execution aspects.

For bigger projects, VDI 2221 proposes to run through the whole process recurrently, from prototype to final production-ready product states. In this case, further realization may also mean the step back to a new design cycle. Then, experience and result knowledge has to flow back to step 1 of that cycle (not explicitly shown in figure 10).

4.3. First conclusions for improving the process

The knowledge streams depicted in figures 3 to 10 show a high dependency all along the design process on external knowledge as well as a huge amount of knowledge leaving the process, thereby being potentially lost. From these streams, various starting points for improving the analyzed process can be identified. Three of these points will be described in the following.

4.3.1. Capture and reuse of the external streams

Each knowledge item depicted in the external knowledge-out streams has to be analyzed if and how it could be re-fed to the process via the external knowledge-in streams, see point ① in figure 11.

One principle to achieve this is the systematic explicitation of these knowledge items. This especially applies to all kinds of reasoning behind decisions within the respective process steps. One method to achieve this could be, e. g., to promote documentation standards such as the trade-off diagrams or A3s of lean product development.

4.3.2. Knowledge buildup within the internal stream

Diagram ② in figure 11 symbolizes the internal knowledge build up along the design project. Mapping this curve to the steps of the design process, it gets obvious that the main decision point when selecting the solution principle is based on partial knowledge, only. All knowledge gained afterwards through detailing, prototyping or realization (hatched area in the diagram) is either lost for this respective decision or may lead to revisiting that decision, later on.

To avoid these problems, a better fit of the knowledge build up curve and the design process has to be aimed for. This could be done, e. g., by making the knowledge curve steeper through the inclusion of modeling and simulation activities into the early process steps, or by postponing the principle decision to a state of more complete knowledge, such as done

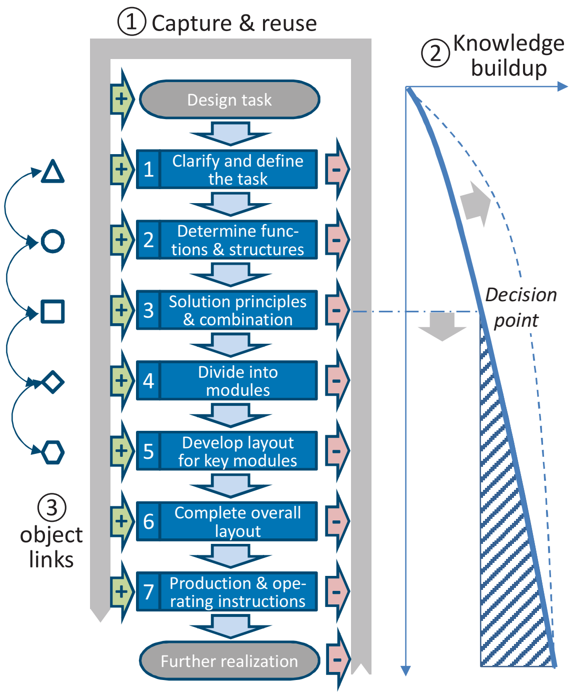

Figure 11:
Improvement potentials along the product design process

with the set-based engineering approach of lean product development.
Another approach to better capture the knowledge build up within the internal knowledge stream could be to explicitly model the links between the focus objects of the respective process steps, i. e. the requirements, functions, solution principles and realization modules and geometries, see point ③ in figure 11. Similar approaches are currently promoted by engineering IT providers in an effort to better support early systems engineering process steps through IT.

5. DISCUSSION

The application of the design to knowledge concept and especially of the knowledge stream analysis method on the standard design process model of VDI 2221 illustrates the strength of this approach to first identify knowledge-related gaps, flaws and improvement potentials along the process, and then to directly address them. It may thereby also lead to hints for a revision of traditional design methodologies, see chapter 5.1.

Besides the application of the concept on standard process models, as exemplarily shown in this paper, it is also applicable as a process improvement initiative on concrete productive engineering processes. Thus, consequently applying design to knowledge may improve both design processes and results.

Furthermore, understanding knowledge in its entirety, design to knowledge may implicitly lead to also satisfying other design to and design for principles, see chapter 5.2.

5.1. Revisiting traditional design methods

The conclusions in chapter 4.3 have shown that – looked at from a knowledge perspective – traditional design process models such as VDI 2221 may offer potentials for rework and improvement.

According to the three points highlighted in figure 11, such potentials could first lie in more clearly assigning single knowledge-oriented methods to single process steps in order to better support the capture and reuse knowledge stream. Second, the overall process setup has to be questioned and potentially revised in order to better fit and profit from the knowledge built up along the process. Consequences have to be drawn for better tool support of the complete process, starting with the object relations in an underlying information model.

Finally, other improvement potentials can be brought up by further detailing the knowledge-oriented analysis; project management and the inclusion of modeling and simulation process steps being just two examples.

Some of these points have been partially addressed by more contemporary process models such as [6, 7, 8], however not yet to a satisfying extent. Further research will therefor focus on a deeper analysis and synthesis of design methodologies from a knowledge-oriented point of view.

5.2. Design to knowledge in relation to other design to and design for principles

One problem potentially encountered with other design to and design for principles is that, if too much focus is laid on one principle, others may be affected unintentionally or even influenced negatively. As an example, design for disassembly may lead to results not in line with design to cost principles.

With design to knowledge, such unwanted interrelationships and necessary trade-offs do not have to be expected. Quite contrary, honoring knowledge in the way described may foster methods which positively support also other design principles. Generally, design to and design for principles rely on the availability of relevant subsets of engineering knowledge. As an example, improving the capture and reuse knowledge stream from further realization back to earlier process steps will support both the setup and the consideration of better design for manufacturing and assembly guidelines.

Based on this argument, design to knowledge can be understood as a fundamental root design principle; having design to knowledge well established will aid in fulfilling other principles by either facilitating or even superseding them.

Applied on potential revisions of traditional design methodologies as proposed in the previous chapter this means that a knowledge oriented view not only offers a partial, single-sided perspective, but could support a more holistic, beneficial approach to product design.

6. CONCLUSION

In this paper, design to knowledge was introduced as an operationalization approach for the knowledge oriented engineering paradigm. The method of knowledge stream analysis as described in chapter 4 appears to be a powerful tool to identify improvement potentials along design processes. It may be applied to concrete productive engineering processes as well as – as exemplarily done in this paper – to generic process models such as VDI 2221.

Based on these findings, it was argued that design to knowledge can be seen as a primary design principle capable to also support other design to and design for principles – as a root design principle.

Follow-up research will continue to elaborate on the approach described in order to further substantiate the findings when applying it to contemporary process models. These findings will then be incorporated in efforts to revise and improve these process models.

In addition, focus will be put on the applicability of the approach as an analysis and synthesis tool for real engineering processes.

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