COMPUTER AIDED CONTROL SYSTEMS DESIGN FOR HYDRAULIC DRIVES [1]

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Abstract: The design of hydraulic control systems is a complex and time-consuming task that, at the moment, cannot be automated completely. Nevertheless, important design subtasks like simulation or control concept selection can be efficiently supported by a computer. Prerequisite for a successful support is a well-founded analysis of a hydraulic system's structure.
The paper in hand contributes right here. It provides a systematics for analyzing a hydraulic system at different structural levels and illustrates how structural information can be used within the design process. A further central matter of this paper is the *automatic extraction* of structural information from a circuit diagram by means of graph-theoretical investigations.

Keywords: Algorithms and Knowledge-based Software Tools for CACSD, Structural Analysis of Hydraulic Systems, Graph Theory

1. INTRODUCTION

Hydrostatic drives provide advantageous dynamic properties and therefore represent a major driving concept for industrial applications. Large scale hydraulic systems—such as plants in rolling mills and marine technology as well as drives for machine tools—frequently possess a large number of actuators. Therefore, sophisticated interdependencies between single components or entire subsystems may occur, which lead to a variety of challenging and demanding design and control tasks.

Designing large hydraulic control systems implies a systematic procedure. In practice, this is done rather implicitly—based on the intuition and the experience of the human designer. This paper introduces a systematics of hydrostatic drives which reveals their underlying structures as well as relations and dependencies among substructures. The approach allows a thorough structural analysis from which a couple of conclusions can be drawn to support the iterative design process.

A long-term objective is the representation and processing of design knowledge within $^{\text{art}}$*deco*, a knowledge-based system for hydraulic design support (Stein, 1995). Currently, $^{\text{art}}$*deco* combines basic CAD facilities tailored to fluidics, checking algorithms, and simulation methods. The operationalization of hydraulic design knowledge requires a formal definition and automatic extraction of structural information from a circuit diagram; this paper elaborates on both aspects.

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2. STRUCTURAL ANALYSIS OF HYDRAULIC SYSTEMS

The majority of hydraulic systems is designed by exploiting the experience and intuition of a single engineer. Due to the lack of a structural methodology, a thorough analysis of the system structure is not carried out. Instead, a limited repertory of possible solutions is used, thus making the result highly dependent on the capabilities of the individual. This solution-oriented approach only suits for recurring design tasks with little variation.

In the following, a systematics of the structural set-up of hydraulic plants is introduced which leads to a problem-oriented system analysis. Its application to a hydrostatic drive—given as a preliminary design, e. g.—facilitates a consequent and purposive derivation of structural information, which is necessary to make the system's behaviour meet the customer's demands.

2.1 *Structural levels of hydraulic systems*

The systematics developed here is based on three levels of abstraction at which a hydraulic plant can be analyzed (Vier *et al.*, 1996). The differentiation between functional, component and system-theoretical structure bases on system descriptions of different characteristics (fig. 1). From this distinction results an overall view of how to influence the system's behaviour.

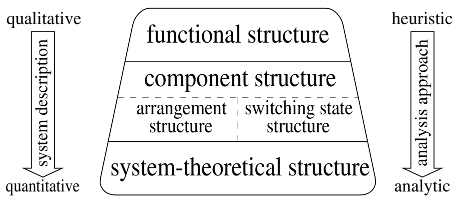

Fig. 1: Structural levels of hydraulic systems.

The **functional structure** shows the fundamental modes of action of a hydraulic circuit by analyzing the different tasks (functions) the plant has to fulfil. Therefore, it represents a qualitative system description. As a basic structural element within the functional structure the *hydraulic axis* is defined as follows (Vier, 1996):

Definition 2.1 (Hydraulic Axis). A hydraulic axis A both represents and fulfils a subfunction f of an entire hydraulic plant. A defines the connections and the interplay among those working, control, and supply elements that realize f.

The subfunction f_i of a hydraulic axis is defined, e. g., by directional load and motional quantities:

$$f_i = \left[\boldsymbol{F}_i^{\mathrm{T}},\ \boldsymbol{x}_i^{\mathrm{T}},\ \dot{\boldsymbol{x}}_i^{\mathrm{T}},\ \ddot{\boldsymbol{x}}_i^{\mathrm{T}}, \ldots\right]^{\mathrm{T}} \quad . \tag{1}$$

The detection of hydraulic axes and their interdependencies admits far-reaching conclusions.

On the level of the **component structure** the chosen realization of a function is investigated. The *arrangement structure* comprises information on the hydraulic elements used (pumps, valves, cylinders etc.) as well as their geometric and physical arrangement (fig. 2 a, b). By the *switching state structure* the entirety of the possible combinations of switching positions is characterized: A valve, e. g., can be open or closed (fig. 2 c, d).

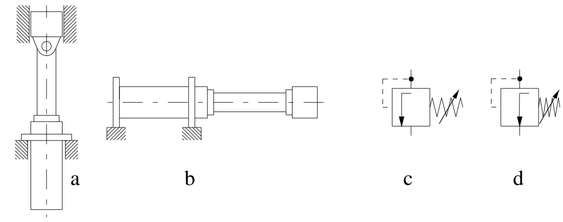

Fig. 2: Examples for arrangement structure (a, b) and switching state structure (c, d).

The **system-theoretical structure** contains information on the dynamic behaviour of both the hydraulic drive as a whole and its single components. Common ways of describing dynamics are differential and difference equations or the state-space form (Schwarz, 1991):

$$\sum_N : \begin{array}{ll} \dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t), u(t)), & \boldsymbol{x}_0 = \boldsymbol{x}(t_0)\ \forall\, t \geq t_0 \\ y(t) = h(\boldsymbol{x}(t), u(t)), & \boldsymbol{x} \in \mathbb{R}^n;\ y, u \in \mathbb{R} \end{array} . \tag{2}$$

The system-theoretical view comprises information on the controlled quantities as well as the dynamic behaviour of the controlled system. Comparing analysis and simulation results with the demands on the performance of the drive, for each hydraulic axis a decision can be made, if open or closed loop control concepts are adequate. In a further step, an appropriate control strategy (linear, nonlinear etc.) can be assigned.

Remarks. While the functional structure yields a qualitative representation, the system description grows more quantitative referring to the component and the system-theoretical level. Moreover, the analysis of the structural set-up shows in which way the behaviour of a hydraulic plant can be influenced (cf. fig. 1): (*i*) The functional structure must be considered as invariant, at first, because it results from the customer's demands. Only if the given structure proves to be unsatisfactory, a modification—resulting from a heuristic analysis approach—is advisable. (*ii*) Note that at the component level a combination of heuristic and analytic methods is required for the variation or exchange of hydraulic elements, which form the controlled system. (*iii*) The system-theoretical level facilitates the investigation of the dynamic behaviour: control theory provides analytic approaches for the selection of a suitable control strategy (output/state-variable feedback), parametrization etc.

2.2 *Hydraulic axes and their coupling levels*

Focusing on the investigation of the functional structure of hydraulic systems, the detection and evaluation of hydraulic axes is of central interest. This analysis contributes to a deeper understanding of the inner correlations of the plant and provides an overview of the energy flows with respect to the functions to be fulfilled.

The definition of the hydraulic axis given in chapter 2.1 bases on the criterion of elements working together in order to fulfil *one* function. Note that several actuators (hydraulic motors/cylinders) may contribute to the same function thus forming *one* hydraulic axis:

a) *Identical subcircuits* which are controlled by one single control element.
b) *Synchronized movements* carried out by open or closed loop control.
c,d) *Mechanical couplings* enforcing a unique behaviour such as guides and gear units.

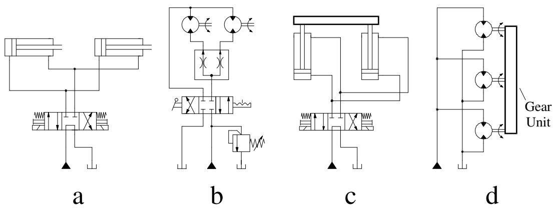

Fig. 3: Hydraulic axes with multiple actuators.

Beyond the consideration of single hydraulic axes, it is necessary to investigate their interdependencies. The following coupling types are worked out:

- *Level 0 or No Coupling.* Hydraulic axes possess no coupling, if there is neither a power nor an informational connection between them.
- *Level 1 or Informational Coupling.* Hydraulic axes which are connected only by control connections are called informationally coupled.
- *Level 2 or Parallel Coupling.* Hydraulic axes which possess their own access to a common power supply are coupled in parallel.
- *Level 3 or Series Coupling.* A series coupling connects hydraulic axes whose power supply (or disposal) is realized via the preceding or following axis.
- *Level 4 or Sequential Coupling.* A sequential coupling is given, if the performance of a following axis depends on the state variables, e. g. pressure or position, of the preceding one in order to work in a sequence.

Illustrations of these coupling types are given in section 4.2.

3. BENEFITS OF A STRUCTURAL ANALYSIS

A structural analysis of hydraulic systems reveals basic design decisions. Especially the functional analysis, which is based on the detection of a system's hydraulic axes, will simplify the modification, the extension, and the adaptation of the system (Stein *et al.*, 1996). The separate treatment of hydraulic axes remarkably reduces the design effort within the following respects:

- *Smart Simulation.* Smart simulation is a human strategy when analyzing a complex system: Subsystems are identified, cut free, and simulated on their own. This reduces the simulation complexity and simplifies the interpretation of its results. Hydraulic axes establish suited subsystems to be cut free.
- *Static Design.* Information on the hydraulic axes' driving concept (open/closed centre, load sensing, regenerative circuit etc.) allows the selection of computation procedures relating the static design. The application of modification knowledge, moreover, has to consider the axes' coupling levels.
- *Control Concept Selection.* The consideration of couplings between input and output variables supplies a necessary decision basis for the selection of control concepts. Analyzing the decoupability matrix $\boldsymbol{D}$ (Schwarz, 1991) yields a common approach, here. Note that the system order that can be tackled is limited. The functional structure analysis provides a separation into: (i) SISO systems, to which standard methods of controller design can be applied, and (ii) coupled subsystems of a reduced order, for which decoupability can be investigated more efficiently or even becomes possible at all.

Note that a smart classification of the couplings between hydraulic axes forms the rationale if to whether a decomposition of a hydraulic design problem is permissible. While subsystems with level 0 or level 1 couplings can always be cut free, additional information is required for parallel, series, and sequential couplings. Example:

Let A, B be two hydraulic axes.

(i) IF coupling$\{A, B\}$ is parallel
AND NOT time-overlap$\{$process$\{A\}$, process$\{B\}\}$
THEN separate_design$\{A, B\}$ is permissible

(ii) IF coupling$\{A, B\}$ is parallel
AND time-overlap$\{$process$\{A\}$, process$\{B\}\}$
THEN separate_design$\{A, B\}$ is prohibited

4. GRAPH-THEORETICAL INVESTIGATION OF HYDRAULIC SYSTEMS

Key objective of the topological analysis of a hydraulic system is the detection of its underlying functional structure. The functional structure is reflected by the hydraulic axes along with the coupling of these axes.

The couplings between several hydraulic axes A_i are of a transitive nature. If A_1 and A_2 are coupled, and if A_2 and A_3 are coupled, then A_1 and A_3 are coupled as well. The coupling level is prescribed by the weakest coupling.

The main working document for a designer is the technical drawing, and there is no tradition or standardized method to additionally specify the functional structure of a hydraulic system. This situation emphasizes the need for an *automatic detection* of the desired structural information.

4.1 *Basics*

The detection of hydraulic axes as well as the couplings between these axes relies on graph theoretical considerations. In this connection we use the following definitions of graph theory in the standard way (Cormen *et al.*, 1990; Jungnickel, 1990), which are illustrated in figure 4:

(1) A *multigraph* G is a triple $\langle V, E, g\rangle$ where $V, E \neq \emptyset$ are finite sets, $V \cap E = \emptyset$, and $g : E \rightarrow 2^V$ is a mapping, with $2^V = \{U \,|\, U \subseteq V,\ |U| = 2\}$. V is called the set of points, E is called the set of edges, and g is called the incidence map. [2]

(2) A graph $H = \langle V_H, E_H, g_H\rangle$ will be called *subgraph* of $G = \langle V, E, g\rangle$, if $V_H \subseteq V$, $E_H \subseteq E$, and g_H is the restriction of g to E_H. A subgraph will be called an *induced subgraph* on V_H, if $E_H \subseteq E$ contains exactly those edges incident to the points in V_H. For $T \subset V$, $G \backslash T$ denotes the subgraph induced on $V \setminus T$.

(3) A tuple $(e_1, \ldots, e_n)$ will be called a *walk* from v_0 to v_n, if $g(e_i) = \{v_{i-1}, v_i\}$, $v_i \in V$, $i = 1, \ldots, n$. A walk will be called a *path*, if the v_i are mutually distinct. Instead of using a tuple of edges, a walk may also be specified by a tuple of points, $(v_0, \ldots, v_n)$.

(4) G will be called *connected*, if for each two points $v_i, v_j \in V$ there is a walk from v_i to v_j. If G is connected and $G \setminus v$ is not connected, v establishes an *articulation point*. The maximum connected subgraphs of G are called *connected components*.

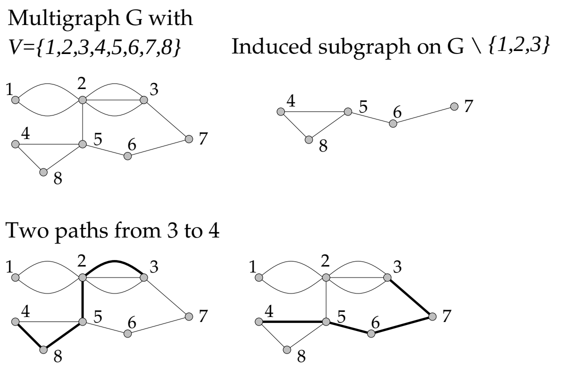

Fig. 4: Illustrations of the graph definitions.

[2] Multigraphs instead of graphs must be used here since components of a hydraulic system may be connected in parallel. Also note the restriction to finite graphs.

To work with a hydraulic circuit C as an ordinary multigraph $G(V, E, g)$ a mapping rule is required. Such a mapping defines for C its *related hydraulic graph* $G_h(C)$.

Definition 4.1 (Related Hydraulic Graph). Given is a hydraulic circuit C. Its related hydraulic graph $G_h(C) := \langle V_C, E_C, g_C\rangle$ is defined as follows. (i) V_C is a set; each non-pipe component of C is associated one-to-one with a $v \in V_C$; V_C does not contain other elements. (ii) E_C is a set; each pipe component of C is associated one-to-one with an $e \in E_C$; E_C does not contain other elements. (iii) $g : E_C \rightarrow 2^{V_C}$ is a function that maps e onto $\{v_i, v_j\}$, if and only if there is a pipe between the components associated with $\{v_i, v_j\}$, and if e is associated with this pipe.

Figure 5 contrasts a hydraulic circuit and its related hydraulic graph. The labels in the graph shall underline that there is a one-to-one mapping between the elements of the graph and the components of the hydraulic circuit.

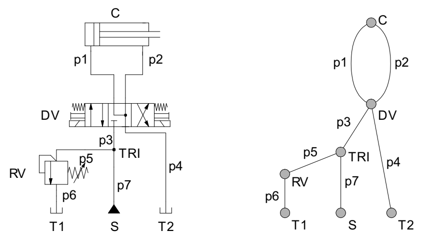

Fig. 5: Sample circuit with its related graph.

Remarks. For each hydraulic circuit C there exists exactly one related graph $G_h(C)$. Note that g performs a topological simplification of C:
(i) g_h comprises the substructures within directional valves down to one single point v, hence making all connected pipes incident to v. (ii) Variations of the topology coming along with valve switching are neglected. (iii) Directional information that results from the behaviour of particular hydraulic components is dropped.

4.2 *Hierarchy of Coupling Types*

In order to determine those components of a hydraulic system that belong to a particular hydraulic axis A, couplings between A and other axes must be identified as such. A prerequisite for the detection step thus is a classification of possible coupling types. The following classification scheme gives a precise graph-theoretical definition of the coupling levels introduced in section 2.2.

Definition 4.2 (Coupling Types). Given is a hydraulic circuit C containing two sub-circuits A, B, which realize two different hydraulic axes. Let $G_h(C) := \langle V_C, E_C, g_C\rangle$, $G_h(A) := \langle V_A, E_A, g_A\rangle$, and $G_h(B) := \langle V_B, E_B, g_B\rangle$ denote the related hydraulic graphs of C, A, and B respectively.

- *Level 0 or No Coupling.* If $G_h(C)$ is not connected, and if $V_A \cap V_B = \emptyset$, then the hydraulic axes A and B are not coupled.
- *Level 1 or Informational Coupling.* Let $\{e_1, \ldots, e_n\}$ be in E and each e_i associated with a control line within C. If $G_{h'} := \langle V_C, E_C \setminus \{e_1, \ldots, e_n\}, g_C \rangle$ is not connected, and if $V_A \cap V_B = \emptyset$, then the hydraulic axes A and B are informationally coupled (cf. figure 6).

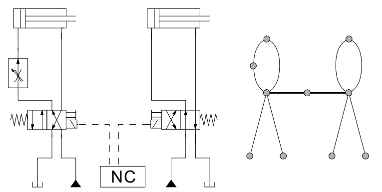

Fig. 6: Circuit with informationally coupled axes.

Note that control lines can be of hydraulic, pneumatic, or electrical type.

- *Level 2 or Parallel Coupling.* Let v_a, v_b be two points in V_A and V_B respectively. Let P_{ab} comprise all power paths[3] from v_a to v_b; i.e., each $p \in P_{ab}$ is of the form $(v_{p_0}, \ldots, v_{p_n})$, $v_{p_i} \in V_C$, $v_{p_0} = v_a$, $v_{p_n} = v_b$. Then A and B are coupled in parallel, if points v_a, v_b exist such that the following conditions hold:
  - (i) $\forall p \in P_{ab} \, \forall v \in p : v = v_a$ or $v = v_b$ or v is associated with an auxiliary element.
  - (ii) There exist two paths, $p_a = (v_a, \ldots, v)$, $p_b = (v_b, \ldots, v)$ where v is associated with a supply element and p_a (p_b) contains not v_b (v_a respectively).

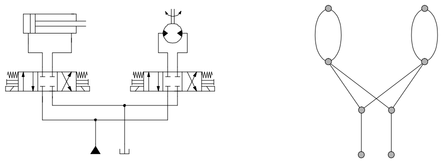
Fig. 7: Circuit with axes coupled in parallel.

- *Level 3 or Series Coupling.* Let v_a, v_b be two points in V_A and V_B respectively. As above, P_{ab} comprises the power paths from v_a to v_b. Then A and B are coupled in series, if v_a, v_b exist such that the following conditions hold:
  - (i) $\forall p \in P_{ab} \, \forall v \in p : v = v_a$ or $v = v_b$ or v is associated with an auxiliary element.
  - (ii) Let v be associated with a supply element. Then either each path $(v_a, \ldots, v)$ contains v_b or each path $(v_b, \ldots, v)$ contains v_a.

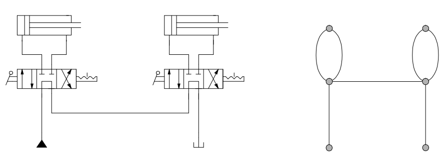
Fig. 8: Circuit with axes coupled in series.

[3] The term "power path" shall express that no edge within a path $p \in P_{ab}$ is associated with a control line.

- *Level 4 or Sequential Coupling.* If $\exists v \in V_A \cap V_B$ that is associated with a control element,

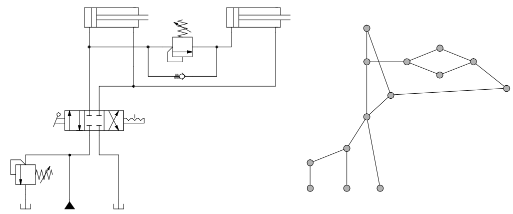
Fig. 9: Circuit with sequentially coupled axes.

the hydraulic axes A and B are sequentially coupled. Figure 9 gives an example.

4.3 *Discussion of the Coupling Types Definition*

The definitions for parallel and series coupling rely on the graph-theoretical definition of a *path* (and not of a walk). Consider the following figure 10: No path from point a to point b contains a control or a working element.

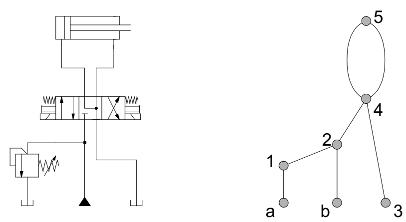

Fig. 10: Paths and walks in a hydraulic graph.

A *walk* from point a to point b, on the other hand, is allowed to contain duplicate points. E. g. the node sequence $(a, 1, 2, 4, 2, b)$ both establishes a walk and contains a working element. However, $(a, 1, 2, 4, 2, b)$ violates the path definition.

Condition (i) of the definition for parallel and series coupling types ensures that v_a and v_b are not associated with an "inner" component of a hydraulic axis. Condition (ii) of the parallel coupling definition ensures the parallel nature of the linkage: From v_a (v_b) a supply element can be reached without crossing v_b (v_a).

By contrast, condition (ii) of the series coupling definition states that no two paths can be found, which are independent in this way.

The detection of hydraulic axes is a sophisticated job, which cannot be tackled by a simple ad-hoc approach. The next section presents the basic concepts of a detection procedure.

4.4 *Detecting Hydraulic Axes*

Starting point is a hydraulic graph $G_h(C)$ of a circuit C. The approach to the detection of hydraulic axes consists of three main steps:

(1) *Graph Condensation.* Within the condensation step, a circuit's hydraulic graph G_h is reduced in order to simplify the accessibility analysis. Loosely speaking, G_h is "stripped"

from components that do not form a hydraulic axis backbone.

(2) *Accessibility Analysis.* Matter of the accessibility analysis is the application of the definitions to determine both the hydraulic axes and their couplings in the condensed graph.

(3) *Graph Extension.* This step addresses the completion of an axis in the condensed graph relating the original hydraulic graph.

Depending on the circuit in hand, the condensation step in turn may contain several sub-steps:

- *Condensation by Control Path Deletion.* Control paths establish no isolation characteristic for hydraulic axes. They can be found (and removed) easily in G_h.
- *Condensation by Dead Branch Deletion.* A dead branch is a subgraph whose nodes are not associated with control or working elements and whose connectivity is 1:

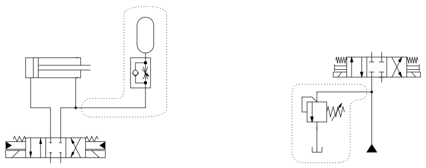

Fig. 11: Two examples for a dead branch.

- *Condensation by Particular Component Deletion.* There exist a few non-auxiliary components, whose corresponding nodes can be removed from G_h without a sophisticated investigation. The check valve is an example for such a component.
- *Condensation by Loop Resolution.* Cyclic structures and components connected in parallel are not necessary for detection purposes if they neither contain nor control a working element. Figure 12 gives a few examples.

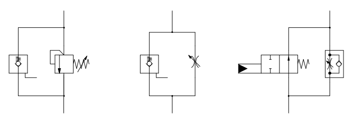

Fig. 12: Examples for loops that can be cut.

Let G'_h denote the condensation of G_h, achieved by the steps outlined above. The accessibility analysis is grounded on G'_h and the definitions of section 4.2. While a level 0 or a level 1 coupling can be detected easily by simply applying the definitions, the detection of the other coupling levels requires the following steps:

- Introduction of candidate axes.
- Determination of the candidate axes' working elements.
- Application of the definitions of section 4.2.

5. CONCLUSION

The contributions of this paper are twofold: (*i*) It discusses the role of structural information when designing hydraulic control systems, and (*ii*) it provides both a systematics and theoretical foundations for the automatic detection of the functional structure from a hydraulic circuit diagram.

The effort in formalizing and detecting structural information is justified: It is a prerequisite when operationalizing hydraulic design knowledge within a knowledge-based system. In particular, information on a system's hydraulic axes along with their couplings shall be exploited in the art*deco* system during the following tasks: simulation, demand interpretation, control concept selection, and circuit diagram modification. Overall objective is the development of a software tool that goes beyond simulation tools currently used for hydraulic control systems design.

Related to this paper, our current research covers the following core aspects:

Development of Graph Algorithms. There exist no standard graph algorithms to tackle the outlined structure detection problem. Thus, suited algorithms, which are based on a circuit's hydraulic graph representation, are developed and integrated in art*deco*.

Formalization of Design Knowledge. Those parts of a human expert's design skill that explicitly refer to structural information are identified and formalized with respect to their processing in art*deco*. The two rules, shown in section 3, represent a small example for this kind of knowledge.

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