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VIRTUAL PROTOTYPING OF POSITIONING AND MEASUREMENT SYSTEMS FOR HIGHEST PRECISION APPLICATIONS

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1. 1. Introduction

The phase oriented view of the design process distinguishes three abstraction levels with established representations (functional structure, solution principles, embodiment/detail design). Mostly computer aided design systems start in the phase of embodiment design. This is insufficient for a phase-overlapping design of heterogeneous systems. Furthermore it is not possible to propagate changes made in the embodiment design back to the models in the earlier phases efficiently. In addition the necessity of computer-based evaluation of the product properties increases with their complexity in all design phases. In the praxis extensive experience in connection with special tools are needed to consider all phases of design because a lacking integration into the CAD working environment of the designer exists. To overcome these problems a phase-overlapping virtual prototyping is needed.
The paper describes a new approach for a phase-overlapping virtual prototyping of positioning and measuring machines for highest precision applications. These kind of machines are being asked to meet the most stringent of specifications in certain fields of application, specifications in respect of accuracy, speed of movement, reproducibility and stability, all to be maintained in precise positioning over increasingly wide areas.

2. 2. Requirements and conditions of the conceptual design phase

An integrated computer aided product design needs consistent models functioning as digital prototypes. The objective of virtual prototyping is to analyse, to test, to optimise and to evaluate design results before the bodily realisation of the product Figure 1.

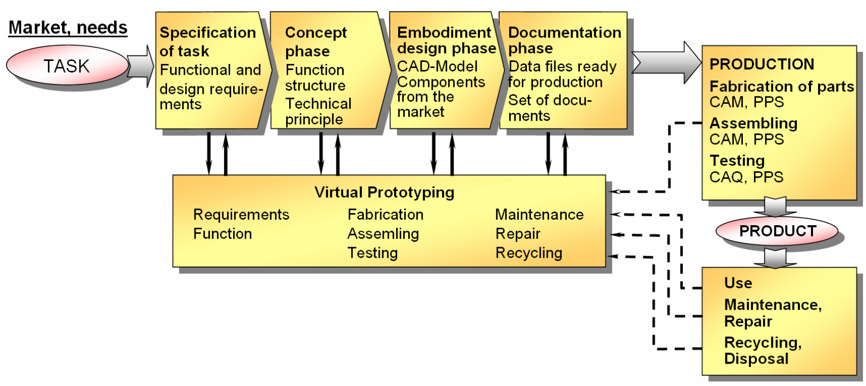


Figure 1. Virtual Prototyping in the product life cycle

All phases of the product life cycle have to be considered during the design process. They cause requirements (constraints) to the function, concept and embodiment design, which have to be presented as virtual prototypes.

The conceptual phase of the design process is important for innovative product development. The creation of new structures starts with the definition of the overall function of the product (Figure 2). The following synthesis steps have three levels of abstraction: functional structure, solution principles and embodiment design.

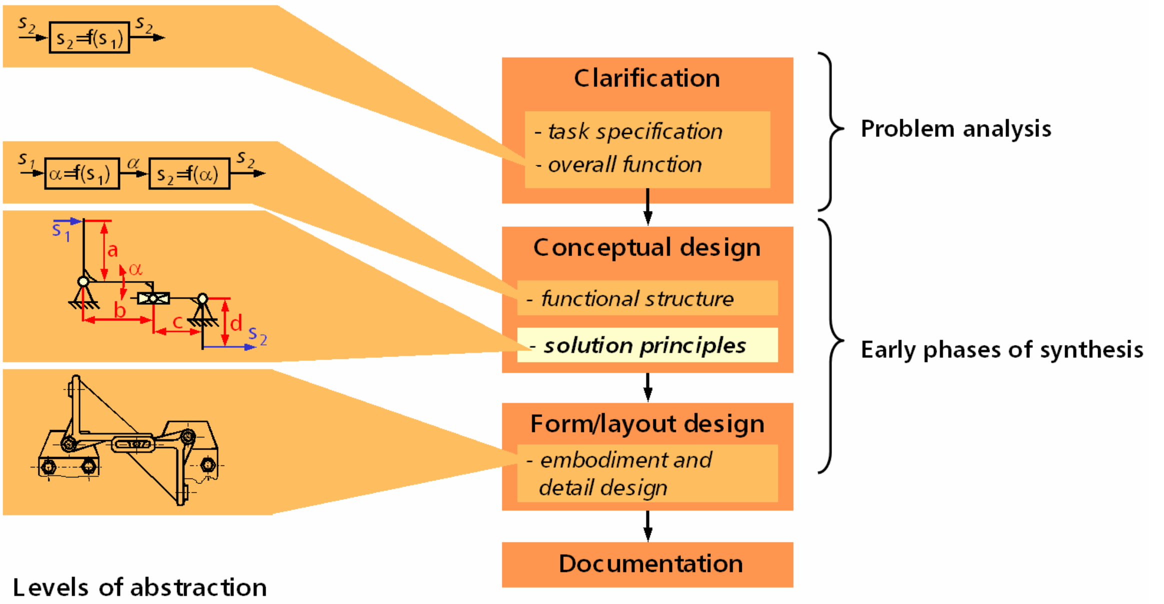


Figure 2. Main phases of the design process

The escrow issue of synthesis is the relation between the given function and the wanted structure of the product [Höhne 2003]:

$$\text{Function} \xrightarrow[p<1]{} \{\text{Structures}\}_i$$

The development of a product structure has two difficulties:

- The determination of solutions (product structures) is plurivalent. A design task has an unlimited number i of solutions.
- This procedure is affiliated with uncertainty. The synthesis of structures has a degree of probability $p < 1$.

Recognising this conditions computer tools for the early states of product development have to consider the following requirements:

- Realisation of a phase-overlapping multi-stage modelling, which includes the abstraction levels: function structure, solution principle and raw shape design.
- The models have to contain non-geometrical parameters and should be accomplished feature-based.
- A parametric approach is necessary to realise quantitative modifications of the structures and shapes [Shah 1995].
- The model should be independent from degree of complexity of the levels of abstraction.
- The raw shape design should contain the adequate properties (geometry, material, condition) of the product to evaluate the required behaviour of them.
- The model has to consider constraints from the requirements of the design task as well as between the components of the product structure.
- The design tool should be utilisable intuitive.

Such kind of design tools is able to shift design relevant decisions from concrete embodiment design into the early design phases.

3. 3. Phase overlapping modelling

In early design phases three main levels of abstraction (function, principle and embodiment design) can be distinguished, which describe results of the synthesis process. For the development of the phase-overlapping design tool the independence on the degree of complexity of structures on the three abstraction levels is very important. The chosen computer-based approach uses constraint-based modelling in connection with a generic constraint solver. This constraint solver is developed at the University of Ilmenau and supports the generation and robust handling of design variants. Constraint solving in connection with a generic constraint solver is a powerful technique for parametric design of 2D- and 3D-models and fulfils the requirements mentioned above. Constraint-based models consist of parameters (scalar or vector), geometric objects (points, lines, circles,…) and constraints (with geometric semantics and some general mathematical functions), which can be defined as relations between them.

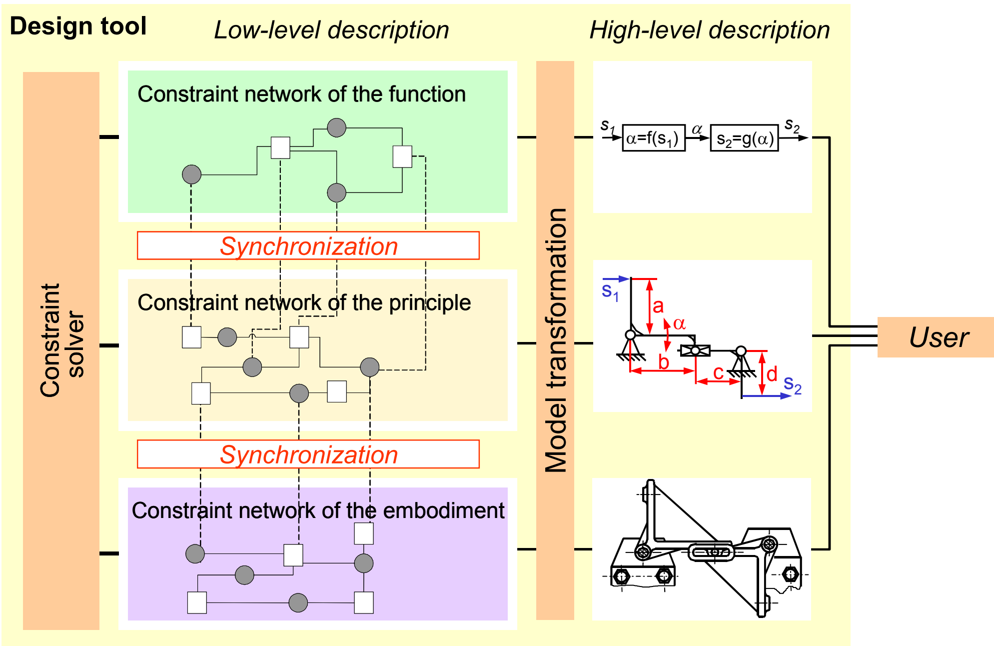


Figure 3. Simplified representation of the level-overlapping constraint network (low-level description) and the according user-oriented description (high-level description)

This allows a suitable description of design objects. Functional, technological (e.g. tolerances, fits), geometric and topological properties can be integrated into one model. For each change of certain parameters or geometric objects in the model the constraint solver generates automatically an appropriate sequence of necessary calculations, which ensures that the changes are propagated and all levels of the model are kept consistent. In this way the values of parameters and geometric objects, defined on the three abstraction levels, are synchronised. Figure 3 shows the constraint networks for those levels.
For the support of user-oriented modelling the constraint-based model with its interrelated parameters must be generated automatically based on the high-level description (Figure 3). To achieve this easy usability an assistant software for catalogue-oriented design is used. It supports the user in modelling of the intended product attributes (e.g. layout / form, material, technological properties) using predefined solution elements (Figure4a and 4b). Such solutions represent components at different levels of description and different quantitative variants to perform functions within a certain range of parameters. The combination of solution elements produces the desired product variants. Based on models, which are defined in the functional or principle stage, suitable solutions for subsequent model

levels can be generated. Necessary bi-directional references between the three model levels are added automatically during the generation. This allows iterations during the design process. In this way the design system enables the user to create alternative solutions, which may be analysed, simulated and optimised regarding several domains of behaviour.

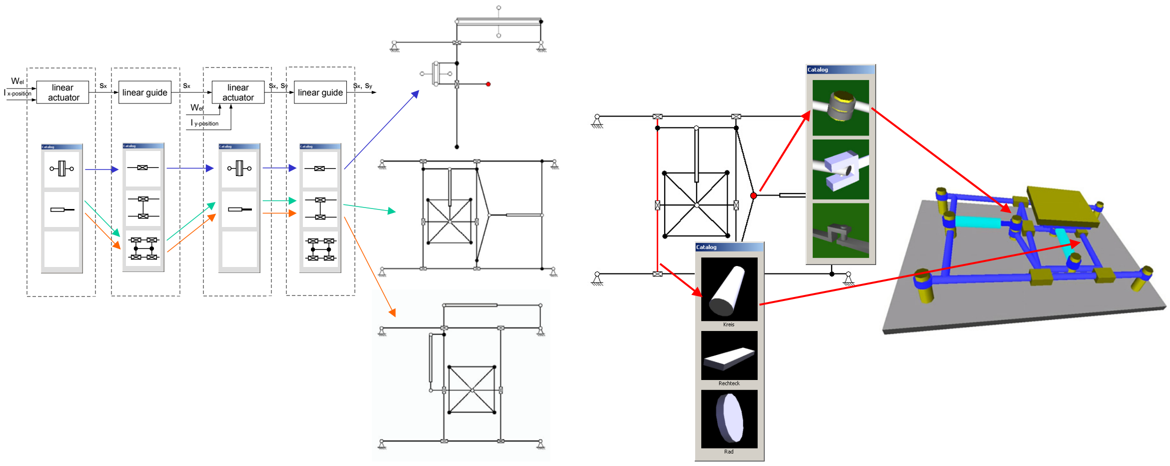


Figure 4. Determination of solution variants by configuration which is a) based on a functional structure and b) based on a solution principle

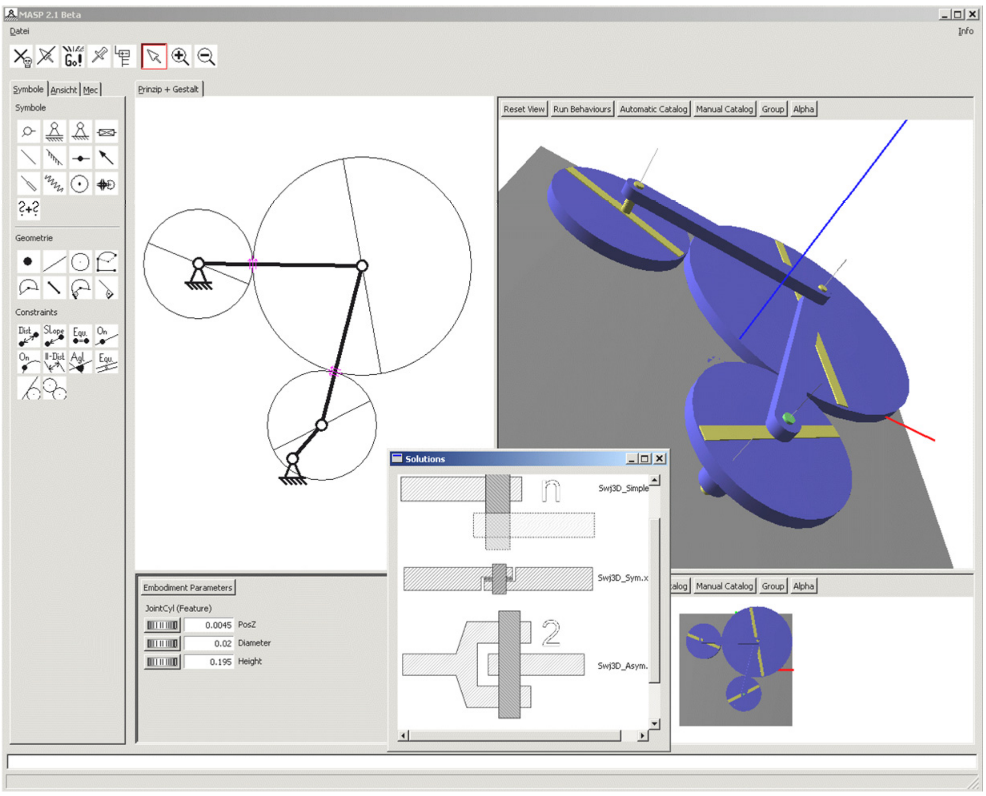


Figure 5. Design system MASP

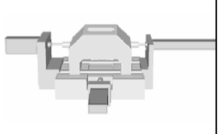
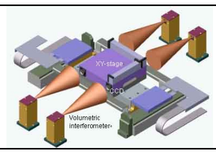
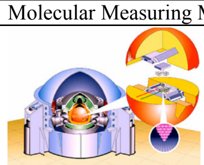
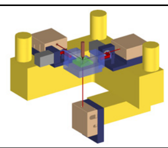
Some of the ideas described in the previous sections have already been implemented in an application called MASP (Modelling and Analyses of Solution Principles, Figure 5) [Brix 2003]. The interactive modelling of solution principles is done by selecting symbols in the context of chosen instruction (e.g. create, delete, modify). For the first steps in embodiment design predefined form elements exist in the mentioned design system (Figure 4b). In this way it is easy to configure models of planar or spherical mechanisms and gears interactively. The variants of the model can be analysed, simulated and optimised related to different properties (e.g. motion simulation using the constraint solver or calculation of static / kinematic quantities by additional algorithms).

4. 4. Virtual prototyping of positioning and measuring systems

The starting point for such system design is the analysis of the technological processes in which the nano-positioning and measuring machines (NPM-machines) are to be made use of. For that purpose it is necessary to describe first of all the operations that must be carried out. These operations depend on the application fields like biotechnology, optics or electronics. For specifying a certain application case a generalised model is needed and used. It describes the overall function of the required machine by means of determination of its interactions with the expected environment, consisting of the operator, other technical systems and the surrounding atmosphere.

The current situation in the area of ultra high precision positioning and measuring machines is characterised by special designs developed for a particular use. There is a variety of single-purpose machines individually designed as unique objects (Table 1).

Table 1. Multiple coordinate high precision positioning and measuring machines (selection)

	Type				
Name	Nano-CMM	Ultra Precision CMM	Molecular Measuring Machine	NMM 1	…
Structure					…
Moving range	10 x 10 x 10 mm³	300 x 300 x 300 mm³	50 x 50 mm²	25 x 25 x 5 mm³	…
Developer	University of Tokio [Takamasu 1999]	BUPE Korea [KAIST 2003]	NIST USA [Kramar 2001]	TU Ilmenau Germany [Hausotte 2002]	…

Analysing functions and structures of the existing systems following properties can be generalised:

- All systems realise a relative multiple-coordinate movement between an object and a tool.
- The movements are controlled in a closed loop.
- The extremely high accuracy is realised by precision guides, prevented from disturbing influences.
- The basis and frames have high stiffness, good long-term stability and minimised thermal deformations.

As a result of this investigation a general functional structure for these machines can be established. In consideration of the objective to serve technologies of the mentioned application fields this function model forms a base for developing a new generation of NPM-machines. It should provide the user with the enabling technology of measuring, handling, processing etc. of nano-scale and macroscopic objects with high precision. To achieve this objective the design of the machines has to fulfil in addition to the generalised properties the following main requirements:

- flexible configurability in relation to the required technological process,
- long-term stability of the machine and good dynamic behaviour,
- wide moving ranges of at least two axis with several hundred millimetres.

In compliance with the well-known rules of modularisation [Hofer 2001], the consequence is to establish a platform consisting of the main subsystems which are shared by all variants of the product family. In the presented case (Figure 6) the frame, the positioning systems consisting of actuator and guidance, the measuring system and the control system forms the platform elements. Tool and object vary according to the technology needs of the application. Therefore the tool and the fixtures of the object are so called non-platform elements designed or selected specially for each type of machine. A function-oriented configuration is indicated because the machines are produced in small numbers.

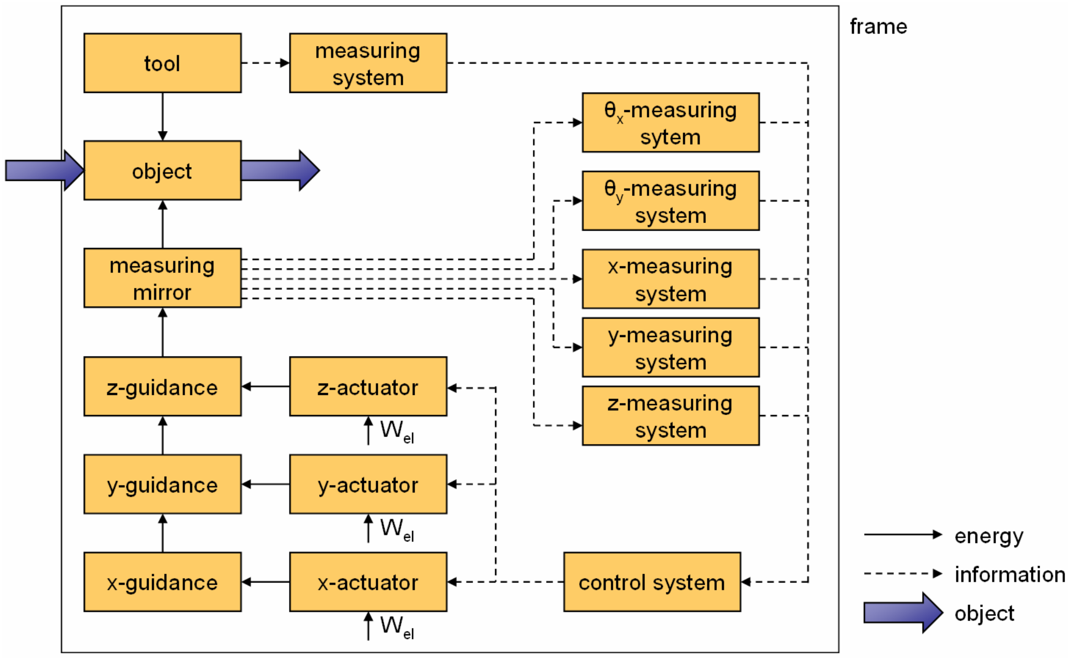


Figure 6. Functional structure of NPM-machine

After specification of the task it is necessary to analyse and determine the technological operations which the machine has to carry out. The designer has to find and to describe the object and the tool(s) as well as the relative movements between them. This investigation specifies the overall function of the machine to be developed. The third stage is the design of structures around the functions. Possible alternatives will be either to build up the structure from sub-functions to match the application or the reduction of an imaginary maximum structure. Considerating the platform concept and the possibilities of virtual prototyping the second option is preferred. The designer can eliminate the not needed sub-functions and it is easy to store this structure by means of a computer.

Table 2. Configuration matrix for nano-positioning and measuring machines

sub-system	variants					
frame	column type	portal type	pillar type	console type	bridge type	…
guidance	roller bearing	sliding bearing	aerostatic bearing	magnetic bearing	spring guidance	…
drive	moving coil	piezo	friction drive with motor	spindle drive with motor	linear step-motor	…
tool	AFM	STM	electronbeam	laserbeam	cantilever	...
measuring system	interferometer	incremental optical	inductive	capazitve	incremental inductive	…
…	…	…	…	…	…	…

The specified functional structure and the determination of the movements are the basis to realise the function-oriented configuartion of the machine. Table 2 has in store solution principles for the platform components. This matrix can be expanded to include new potential solutions. The highlighted fields show the selected components of the machine which will be developed.

The virtual prototyping method [Kunz 2001] is used, beginning in early phases of design, to check both – that the principles will work and that the general form is sound (Figure 7). MASP, a tool for constraint solving [Brix 2003], is used to simulate movements, forces and tolerances of a principle solution. Following tools are that of simulation with multi-body systems and that of finite element method [Hochmuth 2001]. By means of simulation at the initial planning state at the level of principle and rough embodiment design it is possible to make vital decisions on the optimum design.

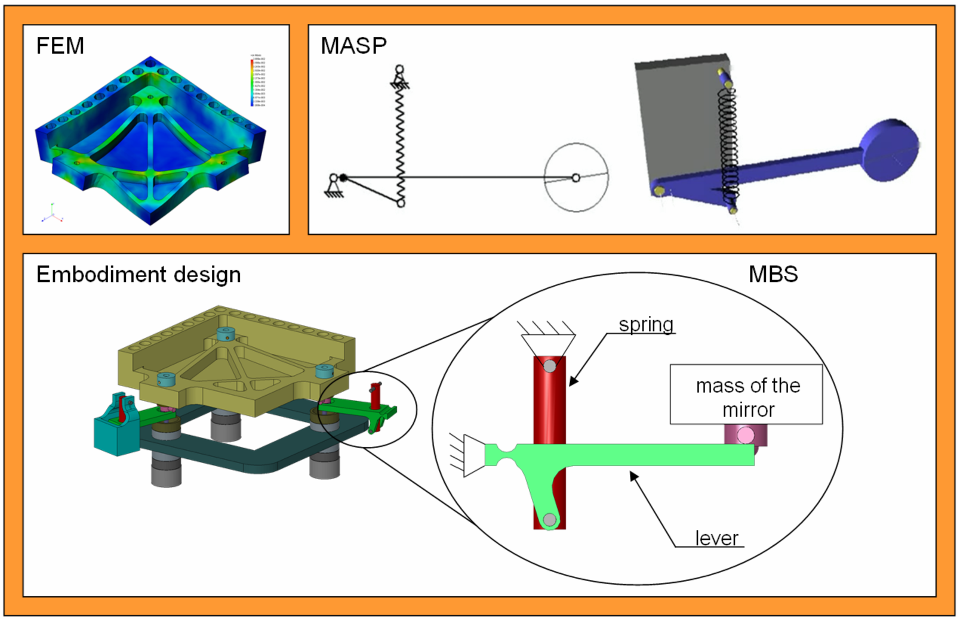


Figure 7. Virtual prototyping and embodiment design

5. 5. Conclusion

The paper presents concepts for a computer-based design of positioning and measuring machines as virtual prototypes to support a phase-overlapping multi-stage design. For a consistent description of the virtual prototypes at various levels of abstraction a constraint-based and catalogue oriented method is used. The modelling follows the described four-stage process of synthesis. It is thus possible even at the initial planning stage to make vital decisions on the possible optimum design. The simulations carried out with the assistance of constraint solving allow decisions about various solutions.

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