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PLANNING DESIGN AUTOMATION SYSTEMS FOR PRODUCT FAMILIES – A COHERENT, TOP DOWN APPROACH

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1. Introduction

Design automation, DA, is a computer based methodology to partly or wholly automate tasks in engineering design by applying modern software technology to do the work of the human designer. The purpose varies from case to case, but usually the intention is to reduce lead time, design costs, to assure adherence to design rules and to allow a high degree of customization. One underlying objective is to free designers from tedious routine work and instead use the human resources for tasks that require creativity, intuition and good judgment. The method can to some extent be applied to original design work, see e g [Bradley et al. 1993], but is much more widespread in industry for use in variant design and it is for this application that the work presented here is intended. Variant design implies that a basic version of the product exists and is proven and that the design task is to create a variant of this by redesigning the basic version to fulfil new requirement specifications.

It is widely acknowledged that the success of an engineering design project depends critically on the first, conceptual phase. If the right decisions are not taken at this stage, it is difficult to make up for this at later stages. The same is true when setting up a design automation system - a sufficient effort must be invested early to clarify the task and define what is to be achieved and what methods that should be applied. However, many projects intended to set up DA-systems tend to introduce specific details of the system early, e g choice of commercial software or choice of computer configurations, resulting in systems that are less than optimal. This work is aimed at the early planning phase where the fundamental and critical issues of a DA system are addressed.

When facing the task of setting up an industrial DA system the perceived difficulty of the task varies strongly form case to case. There are straight-forward cases of configuration or parametric design that are easily understood and the establishment of knowledge base and geometry representation is mainly a question of time and effort rather than ingenuity. But for the more complex tasks it might not be so easy to see how one should master the task at hand. The product related design knowledge might be obscure and incomplete, it might be a mixture of different knowledge formats and domains and it may be complex and with many interdependencies between design variables and features. In such cases companies may feel that the risks of not achieving full system functionality or exceeding cost and time budgets are too great to be acceptable. For decision makers to initiate a new project might appear as running full speed into a dark room and hoping for the best.

The purpose of this paper is to present a coherent path through the critical points of a DA project in order to give a well-structured description of the characteristics of the application and a guide towards the appropriate solutions to be implemented in the DA system. The approach is top-down in the sense that the requirements and problem characteristics are first clarified, whereupon selection of appropriate methods of implementation follows. The procedure described is restricted to the fundamental characteristics of the task and does not discuss questions about e g user-friendliness, maintainability or documentation. All these aspects are of significant importance to success in industrial praxis, but they are of interest only if the fundamentals of the problem first have been solved. It is the intention that by applying the methods described below much of the uncertainty associated with building large and complex DA-systems can be eliminated thus paving the way for more extensive use of DA also for complex design problems. There are several methods for planning DA-systems published like [Stokes et al. 2001], [Hvam 2008], [Cederfeldt 2007], but they are directed towards issues that are closer to implementation.

2. Four industrial cases of reference

The approach is described against the background of recent experience from four industrial cases of applying DA-methods. Two of the companies studied have DA systems in full production since many years, while two are carrying out trials with prototype systems. The companies are described below:

Company A - A large multinational company producing cutting tools and cutting tool holders. These are supplied in several thousand standard variants but also tailor made on customer specifications. Design and offered price for tailor made products can be guaranteed to reach the customer within 24 hours after request thanks to the DA-system. Production preparation and control instructions are also carried out automatically. The system has been in use for more than 20 years.

Company B – A large company designing and building aero engines and components. The company specializes in a number of components that are made in different variants for international OEMs. The DA system is intended mainly to be used at the conceptual stage to optimize the design in terms of costs or specific technical requirements such as minimization of resonance vibrations or residual stresses.

Company C – The company is medium sized and manufactures leisure equipment add-ons for motor cars. One example is roof racks, which consist of standard components except for the fixture plates that attach the rack to the car roof. These plates are tailored to the shape of the car and each new car model requires a new fixture plate. The company designs about 150 new plates each year and has in stock more than 1000 variants.

Company D – This is a medium sized company that manufactures seat heaters for the motor car industry. The seat heaters have a main element of resistance wire that forms a complicated loop. The loop should cover the seat area evenly to give a pleasant warming effect. The company makes 50-100 new wire lay-outs per year for different car models and a skillfully arranged lay-out can save substantial costs. The DA system for the lay-out is linked to the company´s cost calculation system and can thus be used to find the most cost-effective lay-out by trial search using e g different wire types.

3. What is the business purpose of the planned DA-system?

There are many technical aspects of the DA-system that need to be addressed. The starting point however, must always be the expected benefit for the company’s business process. To clarify this fully makes it possible to plan the intended system appropriately in technical terms. We will see that the four reference companies have widely differing intentions with their systems and that these differences reflect in how the systems are built and used.

To clarify what is important and not at an early stage prevents unnecessary effort spent on aspects of the system that are of minor importance. In three of the four cases the DA-system does not produce the final product definition but rather a conceptual design to be used for evaluation and optimization. This fact strongly reduces the demands of detail and also stringency of drawings.

Table 1. Survey of industrial cases

Company	Main purpose	Conclusions for planning DA-system
A	1) On request, to produce a primary design to present to customer and to use for cost calculations	Since the output of the DA-system is fed directly into production and the product shipped to customer without any human intervention, the reliability must be 100%. This requires a stringent quality control of

	2) On order, to fully define product and manufacturing process	software and good program and knowledge documentation. Due to the company's dependence on the system, in-house development is preferred where possible.
B	There are two main purposes: 1) To automatically create specific design features like bosses, flanges and so forth 2) To automatically run FEA in order to optimize design concepts with respect to properties, manufacturability or cost	In both cases the DA-system is used as a support tool for the designers. It has an important role in the business negotiations in that variants can quickly be generated and evaluated on demand from the customer. The use is important for internal efficiency but not critical for product performance.
C	The purpose is to search the product data base of existing fixture plates to see if any of the existing plates are identical or sufficiently close to the new specifications.	All products in the case base have proved to be valid. The DA process is expected to secure that the most suitable case (fixture plate) is chosen, but the result is always evaluated by a product specialist. DA-system supports designers, but is not critical for product performance
D	The purpose is to create primary designs of the wire lay-out to be used for cost calculations in order to identify the most cost efficient solution. On order, the detail design will be made by a human engineer	Sufficient detail and reliability to allow accurate cost calculations is required. The final design is not dependent on the DA-system.

4. The fundamental challenge of design automation

DA should be seen as a specific design method, where computer technology is used to simulate the work of a human designer. Its application is particularly powerful for variant design work within product families. Its application usually means that restrictions as well as new freedoms are introduced compared to the manual process. The introduction of DA consequently implies not only an automation of the manual process, but also causes changes in the way the design is carried out and sometimes even changes of product properties.

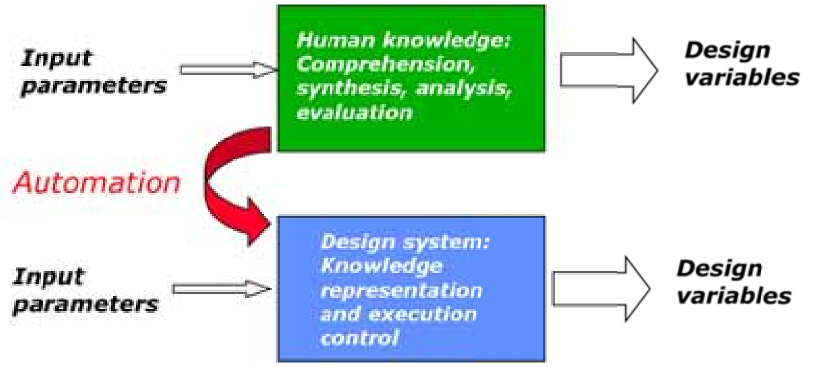

Input parameters
Human knowledge: Comprehension, synthesis, analysis, evaluation
Design variables
Automation
Input parameters
Design system: Knowledge representation and execution control
Design variables

Figure 1. DA-system to simulate the manual design process

Consider Figure 1. The requirement specifications of the design problem are denoted as “Input parameters”, while the resulting product definition is denoted as “Design variables”. For a DA-system to be acceptable it is required that the same input parameters result in solutions that are similar (or better) than what has been achieved by manual designers. However, the way the work is carried out is probably rather different. The human designer relies on e g comprehension of the problem, ability to synthesize and analyse and to evaluate and redesign. This complex and versatile way of reasoning about the design problem is to be replaced by the restricted and rigid workings of a computer. For our type of problems the computer has two fundamental tasks: To represent product knowledge and to control the execution of this knowledge so that it leads to a solution of the design problem. The transformation of the human way of working to that of the computer represents the core problem when building a DA-system.

5. Idealization and modelling of product knowledge

The process of transforming human product knowledge to executable code is often extensive and many gaps or weaknesses in existing knowledge are often revealed. This process is thus a golden opportunity to improve on existing design methods. The approach based on idealization and modelling is well known from setting up simulation programs for physical phenomena in technology. This approach is well applicable also for creating the simulator for design office work. The approach is top-down in the sense that it starts out with clarifying and condensing domain knowledge (idealization) and proceeds with determining a suitable method for representation (modelling). As the last step the characteristic problem structure is determined (see section 6), which leads to a suitable method for knowledge processing.

5.1 Idealization of knowledge

In the traditional design office the product designers usually have many years of experience of their product and its manufacture. The design knowledge is a mixture of experience, stringent rules, company policies, rules of thumb and so on. For the person in charge of building a DA-system it will soon be clear that it is not simply a matter of interviewing designers to extract design rules. Because of the experience and versatility of the engineers, a stringent and exhaustive set of design rules have never been needed before and consequently doesn´t exist. Steps to rectify this situation are discussed below and in figure 2.

There is domain knowledge for the technical aspects of the product that is usually unstructured but accessible. We can call this “raw” knowledge, which consists of various sources of information related to the product and its manufacture. From this large and only partly relevant source of information we need to select the relevant parts, make sure the set of design rules is complete, verify the correctness of these rules, define compromises between conflicting rules, document rules and finally, ascertain that the knowledge base represents the design intent of the company, i e that it is regarded as corporate knowledge. The last objective is verified by a formal authorization process.

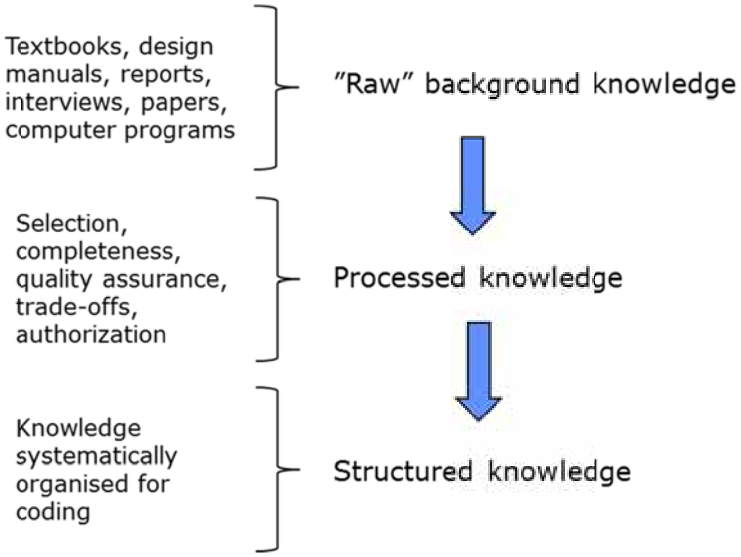

Textbooks, design manuals, reports, interviews, papers, computer programs
”Raw” background knowledge
Selection, completeness, quality assurance, trade-offs, authorization
Processed knowledge
Knowledge systematically organised for coding
Structured knowledge

Figure 2. Idealization of raw knowledge to knowledge ready for coding into DA system

The processed knowledge will now be coded to form the knowledge base of the DA system. For this purpose the processed knowledge is cast into a format that is in accordance with the syntax of the DA system used. The structured knowledge should still be human readable, but structured so that computer coding comes naturally as the next step. It also helps documentation and future maintenance if the knowledge base is structured in a way that seems natural for the designers.

5.2 Classification of knowledge

In order to identify suitable methods for knowledge representation it is helpful to classify the structured knowledge into groups. Each group or category maps naturally to the more common knowledge representation methods. Six classes of product knowledge for DA defined for this purpose were given in [Sunnersjö 2009]. The different categories represent knowledge with varying richness and stringency of background knowledge. It is to be expected that as design rules and methods evolve and mature over time there will a natural progression of knowledge towards the more stringent categories.

The empirical basis for this study of knowledge categories is based on investigations at ten manufacturing companies in Denmark and Sweden. The applications represent high industrial variety, where some applications focus on advanced high-tech products that need to be highly optimised; others focus on tailoring each product to individual customers or to prepare layouts for quotation calculations. The six classes are:

1. **Tacit knowledge.** Unexplained and unarticulated knowledge embedded in the human mind through common sense and experience. Includes intuition, convictions, skills, craftsmanship.
2. **Knowledge based on comparison.** Guide lines based on experiences and insights from comparable products and processes. If previous experiences and lessons learned are stored, understood and taken into account the idea of basing new products on existing, proven solutions is attractive. However, previous experiences might not be applicable or misunderstood which can lead to unexpected malfunctioning of the new product.
3. **Experimental knowledge.** Facts and relations that are reliably established by experiments, e g measured physical properties, performance, efficiency and so on. Within the bounds of the empirical investigations interpolation from measured data to required design data is often acceptable, while extrapolation outside the bounds of experience should be avoided.
4. **Geometrically related knowledge.** In mechanical engineering spatial relationships and geometrical reasoning is often of great importance. Function is often achieved through the geometrical form of products, i e function is embedded in form. Examples where geometrical reasoning is a key factor are styling, packing problems, complex assemblies, load carrying structures and designs where action of flowing media is involved.
5. **Knowledge represented in mathematical form.** When governing design variables can be derived from fundamental physical principles the problem can be represented in a mathematical form. For simplified problems explicit analytical expressions may be available, but for most realistic design problems approximate, numerical computations are required. Design methods in the form of mathematical expressions or numerical algorithms provide physical insight and rigour to the problem and are therefore often preferred when available and realistic in terms of effort, computer execution time and so on.
6. **Heuristic knowledge.** Simple and useful guide lines that are based on experience, reasoning and fragments of theory. Knowledge expressed as facts and rules. Not necessarily based on stringent theory and consequently give poor insight into phenomena and governing parameters. Application outside range of experience may result in unpleasant surprises. When groups of authorities agree on heuristic rules, design praxis is defined. Praxis is a common and important form of documented knowledge; in particular, many commercial and legislative standards (e g ship classification rules, codes for pressure vessels, lifts and trains) belong to this category of knowledge.

The accumulated distribution of the ten companies into the six knowledge categories is plotted in Figure 3. Heuristic knowledge dominates clearly, with mathematical and geometrical knowledge coming second and third.

The “knowledge taxonomy” presented above were used to classify the sets of design rules used by the four reference companies in the present study, se table 2. This classification will serve as input to selection of method for knowledge representation below.

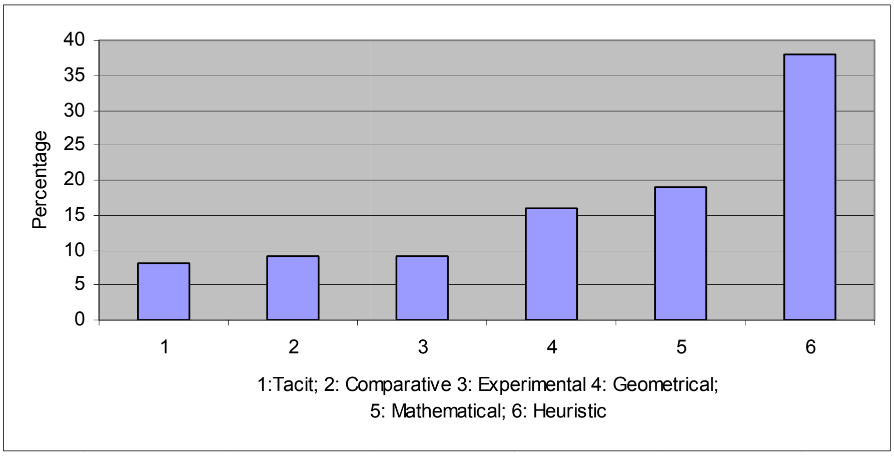


Figure 3. Accumulated distribution of knowledge into six categories for the ten industrial application cases studied, [Sunnersjo 2009]

Table 2. Knowledge categories of the four reference companies

Company:	A	B	C	D
Knowledge category:	Heuristic and geometrical	Heuristic, mathematical and geometrical	Comparative	Heuristic and geometrical

5.3 Representation of knowledge

DA-systems are often based on technologies developed in the field of Artificial Intelligence, AI, which are technologies developed for the purpose of representing, or modelling, knowledge. Figure 4 shows the more common DA-methods grouped into "knowledge based" and "computational intelligence". The third main group is "algorithmic", which is not an AI technology, but traditional programming, because also procedural programming has its place in DA-systems since there are many design problems that are best solved using traditional programming.

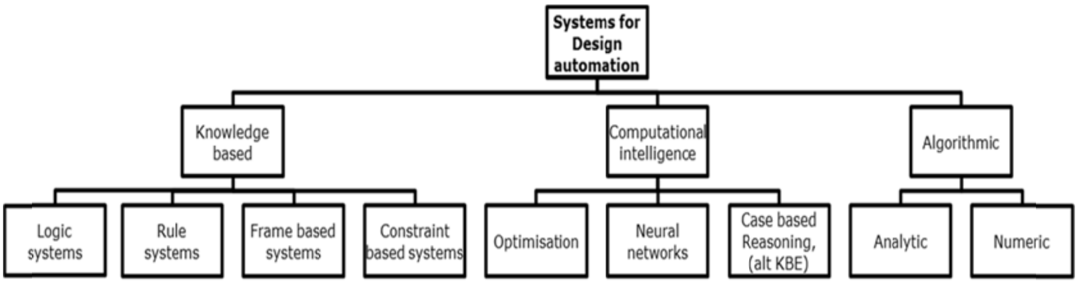
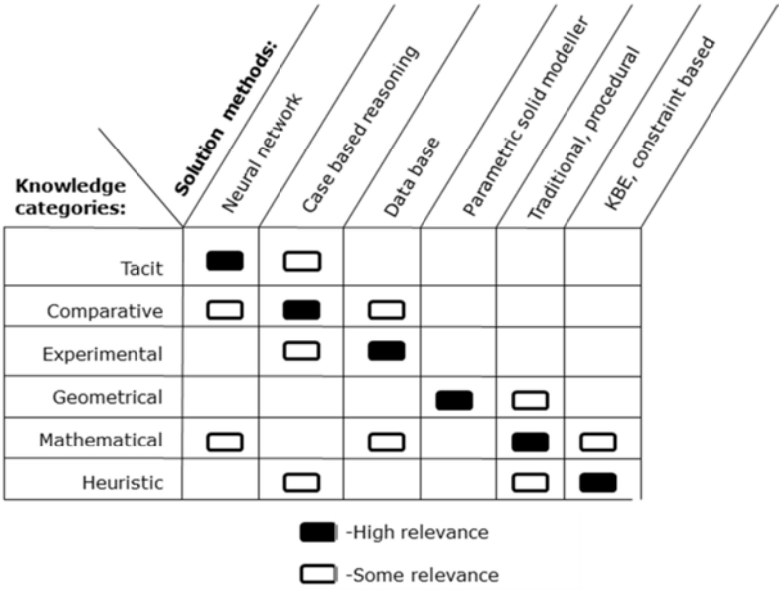


Figure 4. Software technology often used in DA systems. Rule systems are referred to as systems for Knowledge Based Engineering, KBE

The different knowledge categories previously described have a corresponding software method that is well suited to that particular type of knowledge. This mapping between knowledge and modeling tools is discussed in [Sunnersjö 2010] and illustrated in Figure 5. The knowledge from the four reference companies can, using this mapping matrix, be modeled as shown in Table 3.

Table 3. Knowledge modelling methods chosen in the four refeence companies

Company:	A	B	C	D
Modelling method(s):	Rule system, solid modeller	Rule system, solid modeller, FEA	CBR	Rule system, 2D geometry system



Knowledge categories:	Solution methods: Neural network	Case based reasoning	Data base	Parametric solid modeller	Traditional, procedural	KBE, constraint based
Tacit	■	□				
Comparative	□	■	□			
Experimental		□	■			
Geometrical				■	□	
Mathematical	□		□		■	□
Heuristic		□			□	■

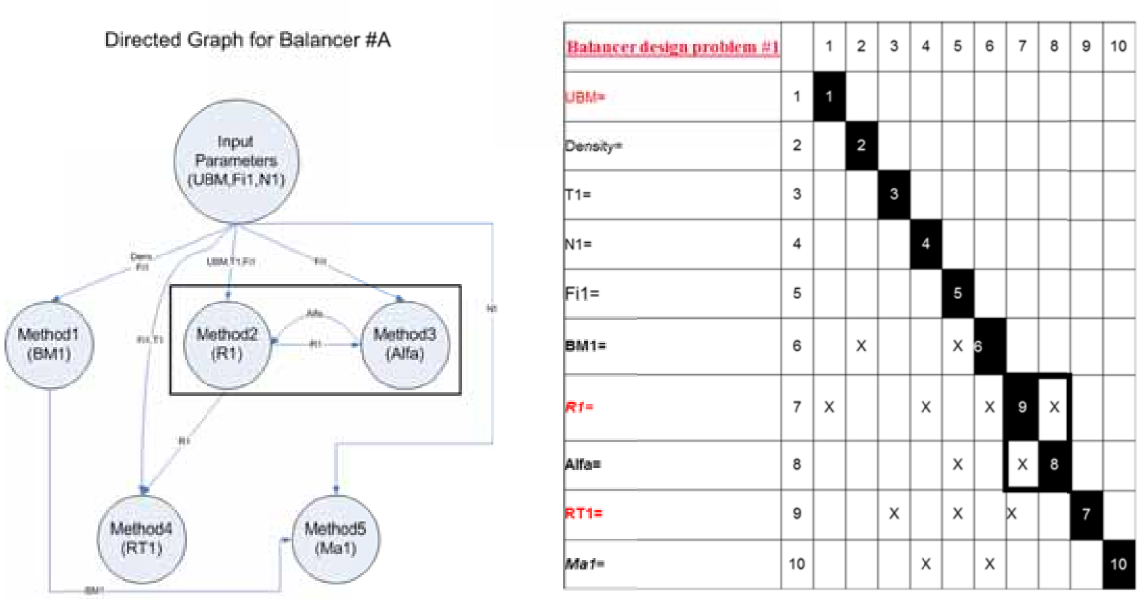
■ -High relevance

□ -Some relevance

Figure 5. The matrix indicates possible implementation methods for different categories of engineering knowledge when planning systems for automatic design

6. Analysing problem structure

Having coded the knowledge base of the DA-system it remains to determine suitable methods for knowledge processing, i e to find methods that activate the relevant sequence of elements of the knowledgebase in order to return the requested solutions. In this context the structure of the knowledgebase, i e how the rules and methods depend on each other and what causalities that should be enforced, is of fundamental importance.



Balancer design problem #1		1	2	3	4	5	6	7	8	9	10
UBM=	1	1									
Density=	2		2								
T1=	3			3							
N1=	4				4						
Fi1=	5					5					
BM1=	6		X			X	6				
R1=	7	X			X		X	9	X		
Alfa=	8					X		X	8		
RT1=	9			X		X		X		7	
Ma1=	10				X		X				10

Figure 6. Example of a directed graph for design calculations (left) and corresponding DSM (right)

6.1 Graph theory and dependency structure matrices, DSM

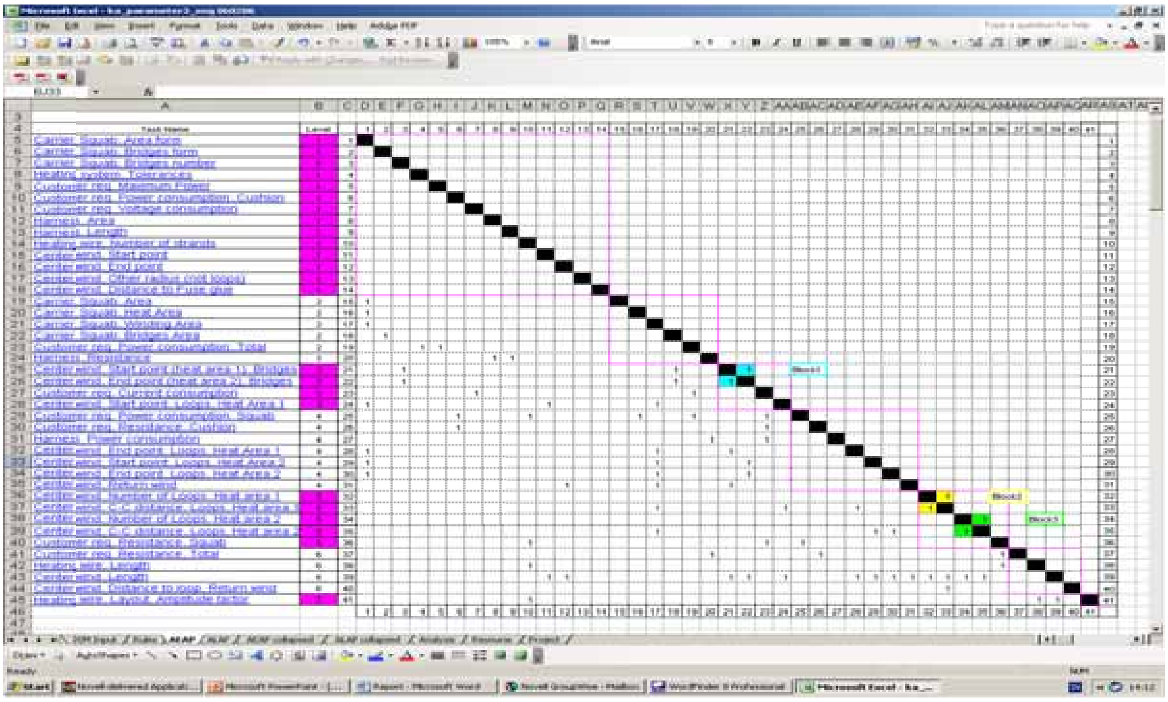
Structures of many kinds can be studied using graph theory, see any standard text book on discrete mathematics. It is a very useful method for planning DA-systems because it gives a clear view of the flow of information in the processing procedure. Figure 6 shows the flow of information (links) and the execution of methods (nodes) for an example problem regarding design calculations for a balancer component.

Graph theory is very useful and illustrative, but for more complex problems the graphs tend to be too complicated and cluttered. An alternative method is then the Dependency Structure Matrix, DSM, see [Eppinger 1990]. DSM maps to corresponding graph as one-to-one, but provides a more compact format and is computer readable. The nodes of the graphs are the rows (and columns) of the DSM and the links of the graph are the “x” of the DSM. Information is defined to always flow downwards in the DSM.

6.2 DA-related conclusions from DSMs

Studying the graph or the DSM give some clear indications for the knowledge processing, see [Sunnersjö 1999]. If the matrix is such that all “x” are below the diagonal, then probably the traditional, procedural software is the most efficient choice. If however there are any “x” above the diagonal, but the rows can be rearranged so that this is no longer the case, then a system based on an inference engine associated with rule based systems (KBE) is more effective from a programming point of view. Further, if any nodes have links that form a cycle, see figure 6, left, variables “R1” and “alfa”. In the corresponding DSM the cycle has the form of a box with mutual dependencies between variables, see figure 6, right. An inference engine can not resolve this problem but will get stuck in an infinite loop. Instead the programmer needs to devise some special solution where the coupled variables and their methods are merged. In some cases (limited search space, preferably integer variables) it may be possible to use constraint programming, a method that can solve also problems with cycles.

6.3 Structural analysis of design knowledge for reference companies



	Task Name	Level	
5	Carrier_Squab_Area form	[illegible]	1
6	Carrier_Squab_Bridges form	[illegible]	2
7	Carrier_Squab_Bridges number	[illegible]	3
8	Heating system_Tolerances	[illegible]	4
9	Customer req_Maximum Power	[illegible]	5
10	Customer req_Power consumption_Cushion	[illegible]	6
11	Customer req_Voltage consumption	[illegible]	7
12	Harness_Area	[illegible]	8
13	Harness_Length	[illegible]	9
14	Heating wire_Number of strands	[illegible]	10
15	Center wind_Start point	[illegible]	11
16	Center wind_End point	[illegible]	12
17	Center wind_Other radius (not loops)	[illegible]	13
18	Center wind_Distance to Fuse glue	[illegible]	14
19	Carrier_Squab_Area	2	15
20	Carrier_Squab_Heat Area	2	16
21	Carrier_Squab_Winding Area	2	17
22	Carrier_Squab_Bridges Area	2	18
23	Customer req_Power consumption_Total	2	19
24	Harness_Resistance	3	20
25	Center wind_Start point (heat area 1)_Bridges	[illegible]	21
26	Center wind_End point (heat area 2)_Bridges	[illegible]	22
27	Customer req_Current consumption	[illegible]	23
28	Center wind_Start point_Loops_Heat Area 1	[illegible]	24
29	Customer req_Power consumption_Squab	4	25
30	Customer req_Resistance_Cushion	4	26
31	Harness_Power consumption	4	27
32	Center wind_End point_Loops_Heat Area 1	4	28
33	Center wind_Start point_Loops_Heat Area 2	4	29
34	Center wind_End point_Loops_Heat Area 2	4	30
35	Center wind_Return wind	4	31
36	Center wind_Number of Loops_Heat area 1	[illegible]	32
37	Center wind_C-C distance_Loops_Heat area 1	[illegible]	33
38	Center wind_Number of Loops_Heat area 2	[illegible]	34
39	Center wind_C-C distance_Loops_Heat area 2	[illegible]	35
40	Customer req_Resistance_Squab	[illegible]	36
41	Customer req_Resistance_Total	6	37
42	Heating wire_Length	6	38
43	Center wind_Length	6	39
44	Center wind_Distance to loop_Return wind	6	40
45	Heating wire_Layout_Amplitude factor	[illegible]	41

Figure 7. DSM for the implemented design process of seat heater, company D

Of the four companies a DSM structural analysis was carried out only for company D. Companies A and B already had working systems and had no need for this analysis. Company C uses CBR which is a technique without any explicit knowledge representation.

The DSM for company D is shown in Figure 6. This analysis proved very useful for the designers who recognised their own workflow more clearly. The DSM also revealed a few coupled variables, that were resolved by merginf whereupon an inference based solver could be used.

7. Conclusions

A theory for how to plan a new DA-system has been presented. The DA-system is regarded as a simulator of the design office. The approach is top-down, starting with idealization of product design knowledge, classification of this knowledge and selection of appropriate modelling (representation) methods. A graph based method is proposed to analyse problem structure and select appropriate knowledge processing method.

The novelty of this work does not lie in the individual methods described, but rather in forming a coherent sequence of steps to identify the fundamental characteristics of the design problem and a logical procedure to select appropriate knowledge processing methods. The applicability and usefulness of the approach has been tested on four reference companies working with DA systems. Our experience is that this approach provides early insight and relevant information that helps in the subsequent work when implementing DA. Having gone through the proposed procedure, much of the uncertainty of a new DA project should have been eliminated. The four cases represent very different applications but the analyses methods presented appear relevant.

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