Analysis of Knowledge Resources and the Methods for its Processing in the Conceptual Design Phase

Jarosław Pruszyński, Konrad Oleksiński, Jerzy Pokojski
Institute of Machine Design Fundamentals, Warsaw University of Technology
e-mail: j.pruszynski@zaprom.pl, koleksin@gmail.com,jerzy.pokojski@simr.pw.edu.pl.

Abstract
The article presents problems related to processing of knowledge in the course of design process, and the methods for dealing with them by the designers while making decisions, with particular attention being paid to the conceptual phase of designing tools in case of customised production. Chapter 1 includes a short introduction and familiarisation with the discussed issue. Chapter 2 briefly outlines the specific features of the company and products that are manufactured. The theoretical scheme of the design process at the conceptual stage typical for the given company is also presented in the article. In chapter 3 theoretical analysis has been supported by examples of real-life design problems resolved in the past. In chapter 4 the authors present their proposals and orientations of their future activities, so as to improve the quality of the knowledge processing in the course of design process.

1. Introduction
The paper concerns the issues of extending conventional engineering design approaches, used in small /medium enterprises, towards conceptual product design [Stjepandic et al., 2015].

Design processes realized by designers are based on their knowledge. The designers’ knowledge results from their formal education, their work and their professional experiences. Personal engineering knowledge of designers evolves together with their professional experience development [Pokojski, Cichocki, 2007a].

An engineering design process consists of two main streams of activities [Clarkson, Eckert, (ed.), 2005]:

1) Activities connected with modelling the reality.

2) Activities analysing the models of the reality and supporting decision making processes.
In most cases designers integrate these two streams in their own way (very often a mental way). They build their models of real life problems while applying concepts of analysis and decision making [Clarkson, Eckert, (ed.), 2005, Pahl et al., 2007]. Their models may range from simple, empirical formulas to very complicated ones, based on physics and multi-equation formulae. As a result, the decision making processes can be set between achieving the status of feasibility and reaching Pareto-optimal solutions [Pokojski, Cichocki, 2007ab].

Nowadays, manufactured products are becoming more and more complex. Consequently design processes associated with these products are also becoming very complex [Stjepandic et al., 2015]. They are realised by multi-person teams who often work in remote locations from each other. Each member of the design team operates on his/her own model and uses specific methods for analysis and decision making.

Both, the models and the methods supporting analysis and decision making are constantly adjusted and improved while designing. These processes are carried out interactively. Each correction is observed with respect to its consequences. The observation can be done during or after the modelling. These processes are strongly connected with the designer’s personal knowledge development [Pokojski, Cichocki, 2007ab].

Design problems solved by different people in the same design process are integrated via common models, analysis and decisions or their parts [Stjepandic et al., 2015]. But due to the separate development of different domains the links between models belonging to different domains are usually less strong than links between models from the same domain. Returning to the design processes realised by designers, we observe that formal models appear during the whole design process. They are more adequate and correct at later stages of the design process. Models which are created relatively early have very strong influences on the next stages of the design process.

Conceptual design models [Clarkson, Eckert, (ed.), 2005, Pahl et al., 2007]. catch and analyse issues which are crucial for the whole project. Often at the conceptual stage different qualitative concepts are checked with regard to their quantitative level by various detailed models.

But in many small/medium enterprises the amount of analysis is not so extreme and many issues are based on existing historical knowledge.

The conceptual design phase is one of the initial stages of the design process, the purpose of which, is to create general solutions to achieve the specific design assumptions/requirements [Clarkson, 2005, Pahl, 2007]. Designing requires the performance of many design activities, as well as using and processing many types of knowledge. Very often, a specific part of it is acquired during this process. It may be stated that the pursued objective is achieved through the changes in the level of knowledge on the given subject. Usually evolution is a multi-stage process.
Information on the effects and causes of effects in the subsequent period is impossible or difficult to identify by other persons than the author of the respective design. A common phenomenon is that even the creator himself or herself is not able to reproduce the path of his or her reasoning at a later date. Even if the knowledge is included in the documentation, which only takes place in case of larger projects, the reproduction is usually incomplete and dispersed [Cichocki, 2001, Court, 1997, Pokojski, 2007]. There is no widespread method used to describe the reasons why the given decisions were made. Therefore, after a period of time some information is lost. This is one of the main reasons for attempts to model and describe the design knowledge [Cichocki, 2001, Clarkson, 2005, Pokojski, 2010, Bracewell, 2009].

The article presents the analysis of the conceptual phase based on the example of a small enterprise engaged in the design and manufacture of sheet metal processing machinery used in the steel construction industry.

The authors started with the case studies in this enterprise.

Chapter 2 briefly outlines the specific features of the company and the products it manufactures.

The scheme of the design process at the conceptual stage typical for the given company is also shown in the article. In chapter 3 two real-life problems that have been solved recently are presented. Chapter 4 includes the identified streams of processed knowledge and solution concept objects, together with the descriptions of their roles and importance levels appearing in analysed case studies. The closing chapter contains summary and conclusions, and it also indicates the authors’ future activities and orientations.

2. Design process characteristics based on the example of a small enterprise

The authors recognise the need to structure the knowledge which is used in the design process. Design knowledge modelling proposals (KMP) are added, in the text, after descriptions of certain types of information and knowledge.

The authors closely cooperate with a company involved in the design and manufacturing, as well as servicing of machines and production lines. The company specialises in the field of equipment used for steel sheet metal processing, as well as production automation systems. The machines are usually custom-made in accordance with the customer’s requirements. The machines manufactured at the company are very often produced only as a “one-off”. Therefore, the approach to the design process is slightly different from the one commonly presented in literature, which, in most cases concerns continuous or mass production [Clarkson, 2005, Pahl, 2007]. (KMP: main attributes of the manufacturing system).
Due to the specific nature of the business mentioned above, not only are the finished production machines specialised “one-off’s” the machines used for production of components or sub-assemblies to complete the final product are also very specific to the industry. Therefore the production capabilities of the company’s manufacturing machines is a very important factor that needs to be taken into consideration during the design process. One of the key factors is to make as many components of the finished machines as possible using in-house machining capability and capacity. (KMP: information concerning components made in the firm).

Another very essential aspect is the cost and time required for making the final solution. Valuation of the given task is nearly always made prior to creation of a final design. It is made based on the analysis of the customer’s requirements. In order to make such a valuation the costs of similar machinery manufactured in the past are taken into consideration, as well as offers of similar solutions from competitors companies are compared if available. (KMP: repository of formulas and algorithms for fast manufacturing costs estimations).

The manufactured machines are usually quite complicated. Apart from mechanical components, also many electrical and electronic components are used, as well as control systems, sensors, etc. Most of the manufactured equipment is also equipped with pneumatic and hydraulic systems controlled with the use of PLCs. (KMP: repository of conceptual and detail models of applied control systems).

Complicated processing machinery involves potential problems related to breakdowns and servicing. The installed processing line/machinery is usually too large to be transported, hence every breakdown that the users are unable to resolve on their own, requires sending a service technician to the customers factory. If a breakdown occurs within the warranty period then it results in generating cost. If a breakdown occurs after expiry of the warranty period then this creates downtime in the customers’ production, which may result in a negative impact on future cooperation. It should be pointed out that at present industrial production (customers of the described company) carry very severe financial penalties related to deliveries of the completed components on time. (KMP: repository of faults and associated issues (parameters, inferences, explanations, case histories).

Frequently it happens that the deliveries of products manufactured by the customers are supplied in the system “just in time”. Each delay in deliveries may result in downtime on production lines or construction sites, which can carry enormous financial penalties. (KMP: “just in time” solutions and associated procedures).

The designers therefore aim at using solutions that are as simple as possible, servicing of which could be easily carried out by the maintenance departments in the customers’ companies. This is also a specific feature
distinquishing the described company from the companies involved in mass production (e.g. auto manufacture). If the machinery is used following the correct operational procedure, sub-assemblies are designed in such a way, that they will require replacement or maintenance after a specified operating period, thus obtaining additional revenue from the post-warranty service. (KMP: repository of applied, recommended standard solutions).

Because the machines are usually manufactured as a “one off” prototypes, it occurs frequently that some components or assemblies have got several versions. The reason for this is the necessity of their redesign or manufacturing from the beginning after the machine is already complete. Redesign is most often required after first attempts to activate the machinery, when not everything works in accordance with the assumptions. (KMP: traceability tools applied to certain components).

Errors during the process of submitting customer’s requirements for the manufacture also take place, as well as geometric constraints at the point of assembly that were not foreseen during the design process. (KMP: repository of check lists – different representations).

An essential requirement is to use as many solutions, components or entire assemblies as possible from previous proven designs. Inclusion of such components significantly reduce the design period, as the existing designs/components only need to be adapted to suit the new concept parameters (e.g. load, speed). (KMP: traceability tools applied to certain components and assemblies).

Selecting a solution that is proven/functioning has got an additional advantage in the form of compilation of feedback from its use. Obviously only solutions that operate trouble-free at the customers’ plants are selected. When making a decision to design a component from scratch there is a possibility of making errors, which in the end will result in the delay of the entire project.

While summing up it should be emphasised that selection of an adequate solution at the conceptual phase in the described company is a multi-stage process. There are some cases where the design process is continued during or shortly after manufacturing of the given equipment. Usually many factors that are often mutually exclusive have to be taken into consideration. The result due to a large number of valuation criteria is always a compromise that seems to be the best at a certain point in time. (KMP: formal multistage descriptions of conceptual solutions developments).

The company has got two design offices and employs 8 persons in total. The first of the offices is involved in designing automation systems and employs 3 persons. In this article, we focus on the work of the second office that exclusively deals with designing mechanical parts. It employs 5 persons. One of the designers has professional experience of approximately 20 years, two have got professional
experience of approximately 10 years. The other two have worked at the company for less than one year. (KMP: formal competences and professional biographies of certain employees).

Work on a new project usually begins with a joint consultation of the designers, who will be involved in the project, along with the person responsible for the contract from a commercial aspect. At this stage the person in charge of the contract submits his assumptions (obtained from the customers’ requirements) to the designers regarding functionality, equipment capability and any other special aspects that the designed equipment should include, as well as any specific requirements in accordance with arrangements with the customer. In case of more complicated projects, direct meetings of designers with the customers are organised. (KMP: formal requirements articulations).

Each of the projects is assigned a chief designer responsible for all the activities. It is always one of the three most experienced members of the team. This results from the fact that these individuals have more knowledge/experience of the process this is a particularly important factor having an influence on the quality of the design process. Unfortunately such knowledge is not available everywhere or recorded while making other projects. Over time the designer acquires certain familiarity with the problems being encountered and only then he or she may become a chief designer for the new task. It should be pointed out that a designer with the longest professional experience acts as a team leader. Such a person very often helps younger co-workers to resolve problems despite the fact that he or she is not in charge of the given project. Such a person also performs a control function, observing and evaluating the progress on an on-going basis. The designer with the longest professional experience is also responsible for ensuring that the specific parts of the project (purpose and manner of division is described in the next chapter) properly integrate with one another at the final stage. (KMP: descriptions of mental models applied during conceptual stages).

The first of the stages required for a new design comprises assignment of designers who will be included in the project. During this meeting the project is divided into smaller sub-projects. It has been common practice that one person is responsible for each of the sub-projects, as he or she may be in charge of several sub-projects or larger tasks. Such a division is functional or geometrical (dimensional). It mainly serves to accelerate the design process – it enables work of many persons in the same time over the aspects regarding sub-projects of the same project task. From that point, each member of a team works independently. When necessary, only meetings are organised, in the course of which general problems regarding the implemented design are discussed. (KMP: description of formal project structures).

We start our considerations at the point when a project has already been divided into sub-projects. Due to the limited size of this publication detailed presentation of the prerequisites accompanying the process of division of a project
into sub-projects has been omitted. We only present the most important components of the conceptual phase of the design process. Sources of knowledge used during the process of conceptual stage of the design phase, as well as the method for selection of proper solutions have been presented in Fig.1.

Fig. 1 The knowledge flows and decision making process – conceptual design process (on base of manufacturer of steel sheet metal processing machines)

The sources of knowledge that the designers use are typical. Information from the product life cycle is applied. Designers use the data from manufacturing, assembly, service and maintenance, as well as information from the detailed design phase. A customer’s requirement that needs to be fulfilled or any other problem that have occurred during design process are a starting point for a decision making process. Created solutions are evaluated in terms of selected criteria. The result of such an evaluation is selection of proper solutions comprising the conceptual design. Each of the decisions made is evaluated making allowance for the following conditions specific for the described company:

- Customer’s requirements
- Production capacity
- Cost/manufacturing period
- Level of complexity
- Use of well-proven solutions/components
3. Real-life problems of conceptual design phase

This chapter presents two real-life problems that the designers have recently encountered. The first of the problems is of a more general nature and regards correct selection of components of a line for manufacturing sheet metal profiles. The second problem describes the need to correctly select components regarding structure and physical restraints to enhance the performance of one of the functions of the line.

The objective assumed by the customer was to design and construct a line that will be able to manufacture 4 types of profiles with a possibility of future development in a manner enabling the manufacture of 6 types of profiles. Another requirement concerned production capacity that had to be maintained at a quite high level, as well as the packing method for the finished products. The customer owned similar lines, however each of them was dedicated to manufacturing only one type of profile, apart from that it did not meet the requirements related to capacity and packing method.

3.1. 1st problem. Configuration of the production line components

Production lines with properties similar to the one described are quite popular and have been manufactured for many years. The conventional method entails steel coil being put into the entry of the machine with a series of forming rolls completing the process with the outcome being finished steel profiles in various shapes and sizes. A standard line consists of the following components: uncoiling device, device for feeding material into profiling machine, profiling machine with cut-off device. The equipment automatically receives material from the uncoiling device which is fitted with a friction brake that prevents excessive uncoiling of the material when the line stops to cut off the finished product at the required programmed length, the process is then continually repeated until the programmed orders are complete. At the beginning, the designers considered making use of the conventional configuration, developing it only for the possibility of working with six types of profiles. However, after making initial calculations it turned out that for the purpose of achieving the production capacity required by the customer, rotational speeds and aggressive acceleration and deceleration changes during the production cycle for the uncoiling and profiling machine would be so excessive that such a configuration of the equipment would have no chance of achieving the correct operation parameters.

The designers had such knowledge due to the fact that they had already encountered many undesirable effects in the past while attempting to increase rotational speeds, acceleration and deceleration of similar equipment.

After much analysis it was decided to replace the traditional friction brake with an electrically operated brake. The method of operation of the cutting device also had to be changed to achieve the required output. In the case of conventional
machines, the cutting process takes place with the material stopping and a static cut. In this case it had been decided to use equipment that is able to cut the material when the line is in motion. The device with a construction similar to a traditional guillotine is designed to move in conjunction with the material (at the same speed and direction). At the appropriate moment, its speed is synchronised with the material’s speed, cutting takes place and afterwards the device returns to its rest position and the process is repeated. Both modifications have significantly complicated the construction and resulted in the increase of costs for the device, which of course has not been a desirable feature. Final concept of line configuration is presented on Fig. 2.

Fig. 2 Line configuration

(KMP: multistage descriptions of developed conceptual solutions, integrated with descriptions of considered variants, decision problem formulations and solutions)

3.2. 2nd problem. Selection of adequate operating principle for the cutting device

The change in the operating method of the line described in the previous sub-chapter together with the required higher production capacity, resulted in a subsequent unfavourable outcome. Traditionally constructed cutting devices are crank mechanisms driven by electric motor with a gearbox. In our application substantial acceleration of the cutting element was required. A new crank guillotine project was significantly heavier than the traditional solutions. It was caused by the
necessity to increase motor power (which as a consequence also required using a larger gearbox) to reduce the cutting cycle time. This modification resulted in substantial increase of the mass of the cutting device. That in turn was very unfavourable due to the fact that the entire device has to be accelerated, so as to enable synchronisation of the speed then stopped and returned to the “home” position. Another significant drawback comprised significantly higher rotational speeds of the crank mechanism, the bearings of which were slide bearings which were used due to large impact forces.

Replacement of the crank mechanism with a hydraulically driven system turned out to be a solution of the above-mentioned problems. The mass of the cylinder (that replaced the crank mechanism) is substantially lower than the mass of the components used to construct the crank mechanism principle. As on previous occasions it resulted in the increase of complications and costs of the device, however other more important goals have been achieved. Both variants of the solution described above are presented in Fig. 3.

4. An attempt to formalize the knowledge at the concept stage

In the publications relating to the raised issues [Hatchuel, Weil, 2009, Kroll, 2013, Nomaguchi, Fujita, 2013]) many approaches and attempts to formalize the knowledge of the conceptual phase can be found. However, none of the attempts, known to the authors, is able to meet the needs of designers at all levels. Based on our research, we think that the model of recording the development of knowledge should be constructed in a way that reflects as close as possible the path of formation of the concept with regard to the chronology of decisions [Nomaguchi, Fujita, 2013]. The model should also consider the argumentation, restrictions, rules and associations that will have an impact on made choices [Hatchuel, Weil, 2009, Kroll, 2013]. A very important factor is also the interaction between individual steps. It should be noted that the conceptual design process is not a template task, so the chosen approach considered as the best at the actual time, may require changes when new circumstances occur. Many of the developed issues of the concept are not finally used in the current project. This does not mean,
however, that they are worthless. It is possible that they will be applied in the future. Therefore, information on such activities should be properly recorded.

For the purposes of this study we use the example of a device for decoiling the sheets from the coil. This unit has already been analysed in some other aspects in the earlier works of the authors [Pokojski, 2010a,b, Pokojski, 2011].

Fig. 4 shows a schematic representation of solutions for selected problems (physical phenomenon and a method for transmitting torque applied to drive the main shaft of the device) proposed by the authors on the basis of experience gained from the work on real designs at the described manufacturing company. To present the dynamics of the development of the design project we used the three graphs illustrating different periods of design of the device. The first graph illustrates the 1990s, the second– the years 2000 to 2010 and the last presents the current approach of designers. On the vertical axes of the graphs we show some problems that had to be solved at various stages of the conceptual design process. The horizontal axes represent the possible versions of solutions of these problems (only those that were considered as applicable). The fields outlined by continuous lines symbolizes the solutions that were implemented for the design and later in production. Solution taken under consideration but no implemented to production are symbolized by fields outlined by dashed lines. Below the graphs we present the schematic changes in selected solutions over the previously mentioned period. Arrows between the symbols of selected solutions show the evolution of decisions.
over the years. The example includes the description of two problems: the selection of the physical phenomenon to the shaft drive and the method of transferring torque on it.

Fig. 5 describes in detail how decisions are made at the stage of conceptual design basing on the example of the physical phenomenon used to drive the main shaft of the coil decoiler.

![Fig. 5 Decision making diagram](image)

The same convention is preserved as in the previous figure, so continuous lines rectangles represent solutions which were decided to implement. While rectangles consisting of dashed lines symbolise the options considered, but not implemented. Arrows mark decisions, oval elements with “MS” symbols in its background mean the multi-stage evaluation system of solutions considered at every process of selection.

The essence of the proposed approach is the multi-stage evaluation process. In our specific case (described company), we can distinguish the following stages of the process:

- Level of requirement compliance,
- Similar solutions in the past project,
- Assembly/Production feedback,
- Manufacturing cost,
- Maintenance/Service feedback,
over the years. The example includes the description of two problems: the selection of the physical phenomenon to the shaft drive and the method of transferring torque on it.

Fig. 5 describes in detail how decisions are made at the stage of conceptual design basing on the example of the physical phenomenon used to drive the main shaft of the coil decoiler.

The same convention is preserved as in the previous figure, so continuous lines rectangles represent solutions which were decided to implement. While rectangles consisting of dashed lines symbolise the options considered, but not implemented. Arrows mark decisions, oval elements with “MS” symbols in its background mean the multi-stage evaluation system of solutions considered at every process of selection.

The essence of the proposed approach is the multi-stage evaluation process. In our specific case (described company), we can distinguish the following stages of the process:

- Level of requirement compliance,
- Similar solutions in the past project,
- Assembly/Production feedback,
- Manufacturing cost,
- Maintenance/Service feedback,
- Required components availability,
- Selection of correct solution.

5. Conclusion

The described problems illustrate how the design process may work in a company involved in the construction of prototype machines. Some of the above-mentioned examples show that the conceptual and detailed phase may overlap or occur multiple times one after the other, unlike in the case of the conventional approach to the subject. It can also be seen that the knowledge resources used in the course of the both phases may overlap in some areas.

As already mentioned in the introduction and in the second chapter the authors recognise the need to structure the knowledge that is used in the design process.

In the near future the authors will aim at constructing architecture and attempting to implement more universal, multi-profile, multi knowledge representation tool that will be able to support the designers in solving the above-mentioned problems.

The future goal of the authors is to build a formal model of the described approach (and its software model) in UML.

Their objective is that the tool can operate on substantially more complex and structured representations of knowledge than the presently known tools based on annotations or any other systems of personal assistant class [Ding, 2009, Lee, 2006, Kitamura, 2004, Aoyama, 2006, Krearon, 2009, Hisarcikliar, 2009, Lenne, 2009, Fruchter, 2009]

References


Cichocki P., Pokojski J., 2001, Metodyka przechowywania wiedzy projektowej w budowie maszyn, IPBM PW.


