Preface

This book presents the results of extensive research in computer-supported decision processes in engineering, carried out over many years by the author and his collaborators. The author has cooperated with designers in Poland and in Germany. Very often there was university–industry cooperation for the building of specific software for certain engineering tasks.

The majority of the concepts, for example "the designer's personal assistant" and the decomposition and coordination of multicriteria decision problems, evolved through cooperation with designers in this field. The author, while working together with them, understood that this group of people is characterised by a strong individualism and that the range of applied approaches and methods is wide.

The most significant influences on the author's opinions through contact with the designers were the lectures he delivered for more than 12 years for post-graduate studies on computer-aided design in machinery. The lectures included seminars which required the creation of concepts for an individual computer support system for decision processes, generally well known to the designers who participated in the lectures. In the theoretical part the characteristics of the actual computer-aided design and engineering (CAD and CAE) tools were depicted, whereas in the practical part the students created concepts of computer environments for the realisation of design projects in their own professional work. The task was confined to the expression of the design process. This was followed by the development of a concept for the implementation of different computer technologies in the next stages of their processes. The lectures were attended annually by 15 to 25 participants, allowing the teacher the opportunity to cover quite a wide spectrum of real industrial design processes. The majority of students worked in machine industries with different production outputs and product ranges: from aircraft components to a production line for the spraying of car bodies, and from the development of mobile aerial systems to the production of lightbulbs. Several concepts worked out during the seminars were later realised in practice.

It remains to be added that the lectures were conducted flexibly and openly and did not aim at systematic design according to a certain design theory. Although elements of different schools were taught, it was left entirely to the students to choose.

Many of the problems that were subjects of the lectures were later picked up and further developed by ordinary students and research students. Looking at the multitude of solutions of the design processes, the author drew the conclusion that the designers' individualism and internal personal factors play an essential role. Because of that it became important to notice the permanent development of individual engineering knowledge, its richness in facets and its constant evolution. Another observation is the omnipresent re-using of previous processes, their forms of description and the adjustment of the modelling. In spite of certain limitations, often creative elements with the freedom to create new processes could be observed. This mostly worked by using well-known tools, that is, existing and reliable sub-processes.

Interesting was the relationship between designing and the multicriteria optimisation methods. It became obvious that the multicriteria optimisation methods presented as decision-making theory were widely accepted in connection with everyday decision problems.

All of this brought forth a palette of applications based on production realities, which existed at least as prototypes. Some found application in real life, some were implemented within larger projects, and others became the beginnings of a product that is still being developed.

Apart from the direct working collaboration there were many discussions, comments and suggestions.

A good deal of the work that formed the backbone of this book was realised by my research students Pior Cichocki and Maciej Gil.

Various problems concerning the computer tools were solved by my colleagues and collaborators of the computer techniques team at the Institute of Machine Design Fundamentals at the Warsaw University of Technology: Janusz Bonarowski, Jacek Jusis, Boguslaw Kozicki, Grzegorz Linkiewicz, Witold Marowski, Stanislaw Skotnicki, and Jerzy Wróbel.

Many problems were solved practically by numerous students, research students and participants of the post-graduate studies.

I would like to thank everyone mentioned above for taking part in the research.

Also many thanks to my “English advisers”, my wife Antonia and our friends Sophie and Chris Klimiuk who made every endeavour to give my book its final shape.

2 The Nature of the Personal and the Team-based Design Process

Every design process is initiated by a specific need. This process normally starts with some ideas. Gradually the designer develops a basic concept which meets the need. He analyses and evaluates developed ideas. He has to create and be precise with his design details. This multistage activity is called the design process. Questions relating to this process are [5, 35, 50, 51, 62, 65, 68, 101, 106, 112, 113]:

- How do individual designers work?
- How do concepts appear?
- How is a concept developed?
- What are the sources of inspiration?
- How are different interactions between connected sub-problems achieved?
- How does the designer handle design process iterations?

As was found by research, designers often do mental modelling. They exploit their imagination and work with pictures in their minds. Then they try to figure out characteristics of the problems. Often, while explaining their task to other people, designers begin to understand the matter themselves. It becomes more clear to them and they find new ideas.

With more complicated problems some designers try to sketch their ideas on paper or use a CAD system. Others build physical models and test their concepts at once in "reality". The third group are quick thinkers who are immediately able to express their ideas on how to handle the problem. Others have to speak with other people. Finally, all the different ways of approaching a project help the designers to understand the main problem of the task and clarify its characteristics.

During this initial stage of the process the designers look for new information and try to form associations with what they already know. Everything is done with the intention of finding a solution to their problem. They do some mental inference.

The designers do their analysis with the help of a multitude of models and tools. The models which are considered could exist only in the designers' minds or be expressed in a more formal way. The designers build the so-called formal models often by using formal methods and formal software.

The human ability to build models and test them is still the key aspect of designing. Specific knowledge is connected with every technique of modelling and analysis. This knowledge decides what analysis can be done, what goals can be achieved and how the design process can look in a particular case.

The sequence of problems considered in the design process reflects the design history and can be a good source of information for solving particular problems. It may also be a source of available plans already applied in a design process.

The knowledge stored by designers is continuously modified. Each project analysis can give impulses for a new articulation or modification of a knowledge chunk.

Designers exploit their own memory for storing different kinds of knowledge or for the evaluation of other knowledge sources by referring to notes and schemes.

Very interesting results with the interdisciplinary empirical studies of engineering design can be found in [5, 22, 35, 50, 51, 67, 100, 106]. The research presented was done in industrial design offices and university laboratories over many years. One of the goals of this research was to answer the following questions from the perspective of our times:

- What patterns of thought do designers use while problem solving?
- What is the influence of formal methodologies?

The results obtained are multidimensional. Details of different design stages, different models, different tools, the influence of computer tools and the way they are used are considered. Very informative are the results of the comparison between designers who are only practitioners and designers who have a methodological education. Along with this are extremely interesting comments about the form of information which is applied during the design process and the way this information is transformed. The observed relationships between individual and team work in real cases are significant, for instance [67]: "in design processes individual work dominates to an extent $>70\%$ compared to $<30\%$ of teamwork."

For us, most significant is the variety of ways that designers do their job at each stage (individually or in a team). We can notice a strong influence of subjective and personal factors. If in addition we think of the knowledge behind every design decision, we see clearly the importance of these personal and subjective aspects; most of the design knowledge has such roots. Environmental conditions can also play a significant role.

If we want to consider a particular design process realised by a particular designer we not only have to understand his actual knowledge-intensive activities, but also some background knowledge concerning his professional experience. In the case of team work this aspect often becomes even more important.

The development of computer technologies has changed the shape and the range of analysis carried out during the design process. It allows classic approaches to be exploited to a wider extent. New methods have been developed which were originally invented as a computer approach. The problem of interaction between man and the computer implementation of a particular method has become very important. The interaction between the designer and the design problem can be considered on different levels. The levels are set on the basis of cooperation between man and computer. However, this classification has a very strong influence on the particular level and the knowledge structure. When we speak with designers they mostly use the following levels:

- Designer–domain problem (e.g., domain knowledge for the class of problems in machine design or mechanics). This is the highest and the most abstract level, which is very well synthesised. The knowledge presented in this context is very valuable. We can observe an articulated knowledge structure, its hierarchy and its dynamic historical aspect. Hereby the designers use analogies and metaphors while explaining. Listening to them, we can almost sense (if we have enough imagination) how two surfaces cooperate in a joint or how one toothed wheel fits into a second one, for example.

- Designer-methods of particular domains (methods which belong to a particular domain and have an acting function). They support the process of achieving valuable solutions. Most of the designers who achieved the first level did their work exploiting relatively wide experience with some models and methods. Each of their cases solved in practice has a knowledge-intensive background. They can present practical knowledge on how to solve a particular problem by giving the evaluation of the whole approach. Additionally they compare this approach with other approaches, indicating their advantages and disadvantages. We can learn how the approach was developed over some years.
- Designer-methods of a particular domain in a programmed form. Today many of the engineering problems are solved with the help of computers. Consequently behind the designers' decisions stand processes or other steps realised by computer systems. This is connected with very practical knowledge assisting in solving design problems with a particular computer code.
- Designer-computer systems, including methods of a particular domain in programmed form. Rarely does a designer use only one single computer tool. Often a variety of tools are used as a part of a larger task. This can be thought of as the building of a code of codes. One of the main technical problems is its integration. However, at the moment, most important is the knowledge of how and why new tasks are created, which is obviously the consequence of new integration ideas.

From a certain stage, most of the design problems are solved with the help of computer systems which allow different computer models of design products to be built. The designer's work is to extract important artefacts which can be formed from his mental models. Then he must "squeeze" them into the frames of existing computer systems.

Later he has to follow the design process and do the same with different analysis, considerations and details; and at every step he has to consider what parts of his mental work can be placed in the formally developed models and descriptions. This is a situation we are always confronted with, irrespective of whether we use computer tools or not. One has more freedom in thought than in action. From this we gather that a design process developed by a designer is richer than its formal representation can ever be.

Let us take an example from machine dynamics.

Example 2.1

The development of computer technologies has a strong influence on the range of analysis in machine dynamics [12, 72, 78, 90]. Many problems previously regarded as complicated have become routine.

However, some classes of problem have been left unchanged by this development. Up to now it is still difficult to store the knowledge of modelling and solving a particular problem. If somebody wants to solve a certain problem in machine dynamics (a particular phenomenon or product) he has to build (or select from earlier considered models) and examine several models. This process can be called problem learning (by the designer). In many cases it is a long and time-consuming process.

The modelling of a car dynamics model means a lengthy period of work for the designer. For the modelling of a specific multibody system, for example, it is necessary to describe a system of bodies, their connections, their parameters and their external forces.

A real car dynamics problem will serve as our example: the stabilising moment of the steering wheel. We started analysing our problem by reviewing relevant literature. We found several descriptions of this problem. There are also some theoretical models and mathematical formulas. They present a part of the abstract knowledge, which gives a general overview of existing problems. However, in the literature there are hardly any examples of described models. It is very difficult to find out which model could be used in our specific situation. All described models are similar to each other as far as their complexity is concerned. So to put in order and complete these pieces of information we arranged meetings with an expert from the domain [12, 78, 90]. The expert has been dealing with simulation models of cars for more than 20 years, therefore he has extensive practice and theoretical knowledge. We obtained from him information about the relevant cases resulting from negotiations with clients, decisions regarding constructions of a new model and the adoption of a new problem to already existing solutions. We were particularly interested in the way he collected data, searched for missing data, and finally assessed the achieved results.

We have noticed that the expert at the beginning of each thread often refers to one of the previous cases. Then he establishes the procedure for the actual case and tries to generalise it. This is how a linear description of problem solving arises. After the expert has presented several cases we notice that there are common points in the set of linear descriptions. We connect these points and we notice that the output reminds us of a maze model. Figure 2.1 shows us how to proceed with the problem. The diagram presents the way of adapting the problem to existing models and the possibilities of building a new model.

The expert divided the problem into several subgroups. These subgroups distinguish the way the problem is perceived: how deeply one wants to analyse it, which situations are taken into consideration, if the driver’s point of view is important in a particular case, or if the research results are to be used in court. When the problem is classified, it is necessary to find out the purpose of the research, what kind of data can be delivered, and the influence of geometry relationships on the final results. Finally, it is important to know who performs the research because some of the developed models are of an enormous value and cannot be disclosed. It should also be remembered that time and financial resources allocated to a project are of great importance. At the end

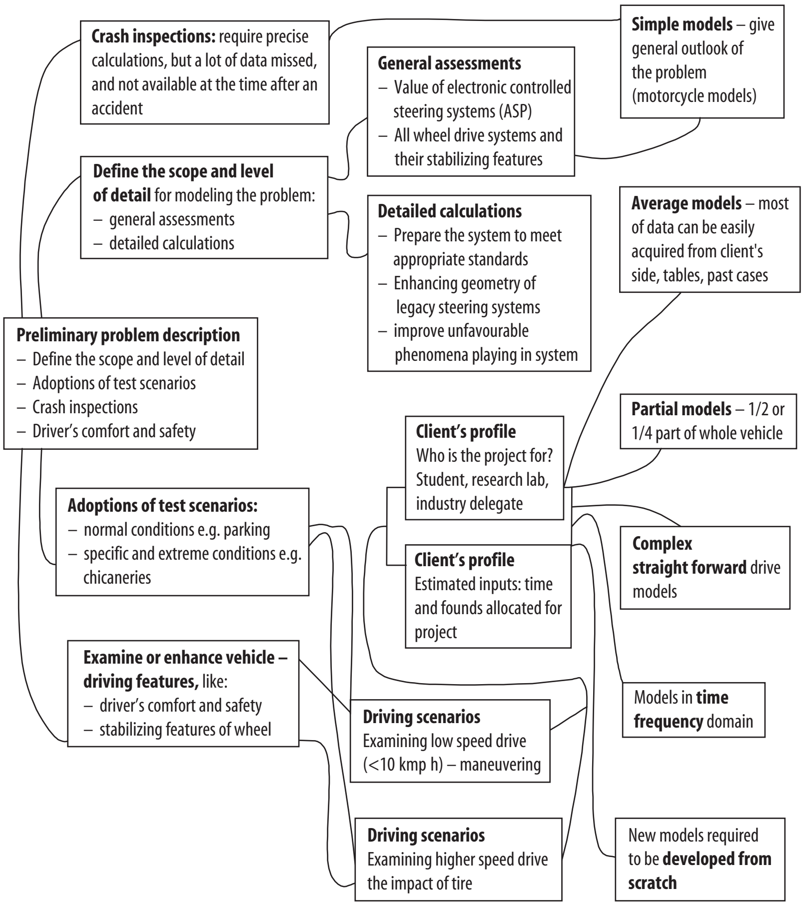

Figure 2.1 Expert's plan for solving car dynamics problem [78].

we can find out which of the existing models could be used in a particular situation, or if the expert would be interested in building a new one.

The results of our research can be described with the following characteristics. The number of degrees of freedom (if referring to multibody systems dynamics) is one of the most significant parameters. In real industrial cases it can amount to a few hundred and result in a multitude of models and analysis. The overall process of analysis can take several months. The designer formulates many rules in his mind and tries to explain the examined phenomena. Parallel to this he validates this knowledge, creates new or better rules and draws final conclusions. For this he uses written notes. At the same time the designer tries to improve his modelling, his methods of analysis and his parameters, and observes all the side-effects. All together it provides an immense field for searching.

In the above example, we presented the way human designers do their work; in a knowledge context and as individuals. The selected problem can be regarded as a specific design task realised by a single designer. Real design tasks consist of several sub-tasks. In his work, a designer does not only try to build the structures of his sub-tasks: parallel to this he also tries to optimise particular problems.

So while he is creating a path of sub-tasks (which reflects the core of building the problem structure) the designer at the same time is trying to select the best parameters for his solutions. In the end he can create a whole sequence of problems belonging to the category of optimisation problems. With every sub-task a multi-criteria optimisation problem created by the designer can be connected by selecting decision variables, constraints and criteria functions. The sequence of optimisation problems – accompanying a path of sub-tasks – can be mutually interacted with via decision variables, constraints or criteria.

However, optimisation problems of different sub-tasks can interfere. We want to clarify this problem by means of a simple example [64, 72].

Example 2.2

Let us assume that our designer has to consider the problem of moving a car with constant velocity and that he has to estimate the quality of the suspension [63, 72, 97]. He builds his first sub-task – a simple dynamic model – linear with two degrees of freedom (Figure 2.2). The equations of motion are

$$\begin{aligned} m_1\ddot{y}_1 + k_1(y_1 - y_2) + c_1(\dot{y}_1 - \dot{y}_2) &= 0, \\ m_2\ddot{y}_2 + k_1(y_2 - y_1) + c_1(\dot{y}_2 - \dot{y}_1) + k_2(y_2 - q) + c_2(\dot{y}_2 - \dot{q}) &= 0, \end{aligned} \tag{2.1}$$

where:

- m_1, m_2 are the sprung and unsprung masses;
- k_1, k_2 are the stiffnesses of the suspension and the tyres;
- c_1, c_2 are the damping coefficients of the suspension and the tyres;
- y_1, y_2 are the displacements of the sprung and unsprung masses;
- q is the kinematic excitation (road roughness).

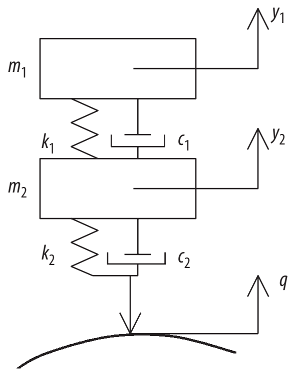

Figure 2.2 Dynamic model of car.

The designer assumed that the excitation is modelled as a stationary stochastic process with zero mean value and spectral density $S(v)$. The spectral density corresponded to the asphalt road and the speed of the car $v = 18$ m/s.

Then the designer selected a set of decision variables (stiffness and damping coefficient of the suspension). The feasible domain is defined in the following way:

$$\Phi_1 = \{(k_1, c_1) : k_{1\min} \le k_1 \le k_{1\max};\ c_{1\min} \le c_1 \le c_{1\max}\}. \tag{2.2}$$

The designer selected two objective functions:

Q_1, the variance of differences between the displacements of the sprung and unsprung masses.

Q_2, the variance of the sprung mass acceleration.

The designer did calculations and obtained results. In Figures 2.3 and 2.4 we have the feasible domain together with the objective space

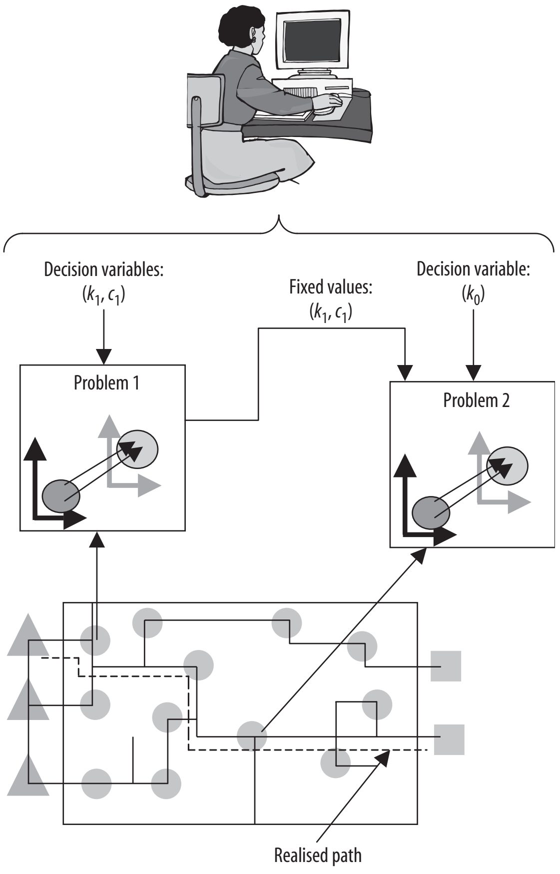

Figure 2.3 Optimisation problem together with maze model.

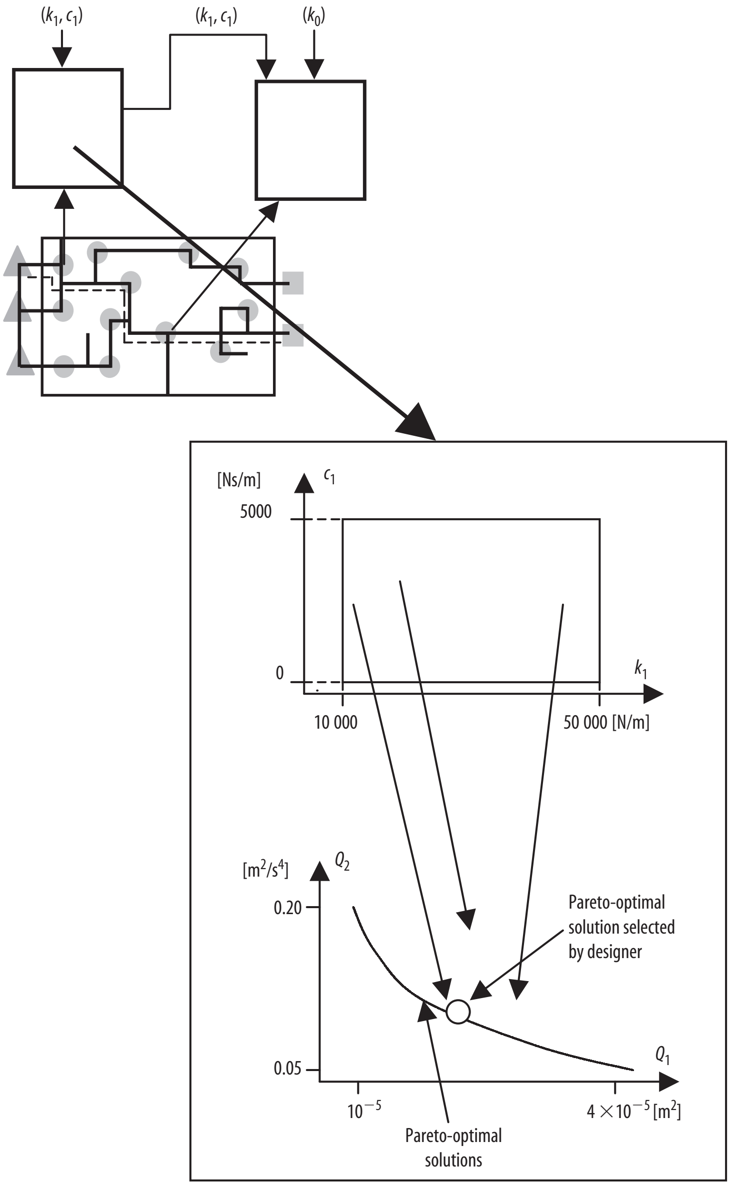

Figure 2.4 Results of first sub-problem.

with final results. As is visible in the objective space we obtain a Pareto-optimal set. This means that the points belonging to this set cannot be improved. After that the designer selected one of the points belonging to the Pareto-optimal solutions.

Later the designer started to consider the next dynamic problem concerning the respective car. He built a model which was suitable for examining how the same car performs when going over bumps in the road. Again he built equations of motion:

$$\begin{gathered} m_1\ddot{y}_1 + F + c_1(\dot{y}_1 - \dot{y}_2) = 0, \\ m_2\ddot{y}_2 - F + c_1(\dot{y}_2 - \dot{y}_1) + k_2(y_2 - q) + c_2(\dot{y}_2 - \dot{q}) = 0. \end{gathered} \tag{2.3}$$

The physical parameters are as in the previous model.

The elasticity force is a function of the spring deflection. The force has the following form:

$$F = \begin{cases} k_0(y_1 - y_2) + (k_0 - k_1)a & \text{for } (y_1 - y_2) \le -a, \\ k_1(y_1 - y_2) & \text{for } |y_1 - y_2| \le a, \\ k_0(y_1 - y_2) + (k_1 - k_0)a & \text{for } (y_1 - y_2) \ge a. \end{cases} \tag{2.4}$$

In this case the excitation was modelled as a single harmonic wave (H – height, D – wavelength, x – horizontal coordinate):

$$q(x) = \begin{cases} \pm \dfrac{H}{2}\left(1 - \cos\dfrac{2\pi}{D}x\right) & \text{for } x \in [0, D], \\ 0 & \text{for } x \notin [0, D]. \end{cases} \tag{2.5}$$

There were the following decision variables:

$$(k_1, k_0, c_1). \tag{2.6}$$

The feasible domain was defined as

$$\begin{aligned} \Phi_2 = \{(k_1, k_0, c_1) : & \; k_{1\min} \le k_1 \le k_{1\max};\, k_{0\min} \le k_0 \le k_{0\max}; \\ & c_{1\min} \le c_1 \le c_{1\max}\} \end{aligned} \tag{2.7}$$

The objective functions were defined as

$$\min_{(k_1, k_0, c_1) \in \Phi_2} \left\{ \max_{t \in [0,T]} |y_1(t) - y_2(t)|,\; |\max_{t \in [0,T]} |\ddot{y}_1(t)| \right\}. \tag{2.8}$$

Calculations were made for the fixed value of k_1, c_1 (from the first considered problem) and as a consequence, the designer obtained the results shown in Figure 2.5. These results were obtained when he considered problem 1 first and then problem 2. We assumed that the designer would solve both problems sequentially, according to their importance. It is also possible that the results which the designer acquired after solving the first problem enabled him to build and solve the next one. This thought process can be observed quite often.

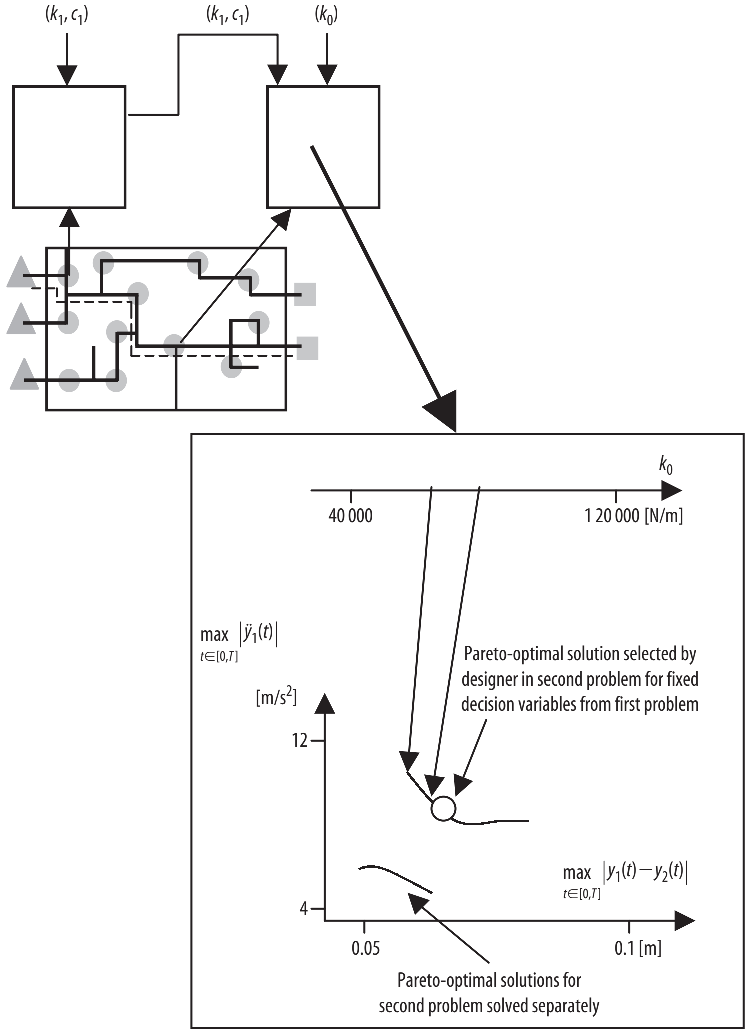

Figure 2.5 Results of second sub-problem.

The number of interconnected sub-problems can be higher than two. According to his knowledge the designer can consider various additional phenomena. Everything depends on the whole design problem and the goal of the design analysis. The sub-task structure of the path and the associated optimisation problems can be created dynamically by the designer.

However, the two interconnected problems presented above can also be considered in a different way. We can treat the two sub-problems as one global optimisation problem. In this case we can build a common feasible domain (Figure 2.6).

As presented in the figure, we have two objective spaces. Now we can observe that in both sub-problems two Pareto-optimal sets are achievable. However, if we analyse the points from the first Pareto-optimal set we will see that the points corresponding

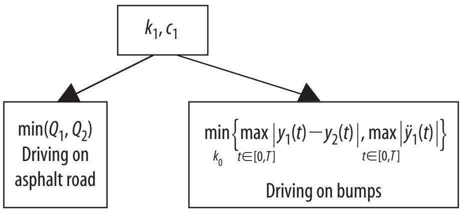

Figure 2.6 Structure of optimisation problem.

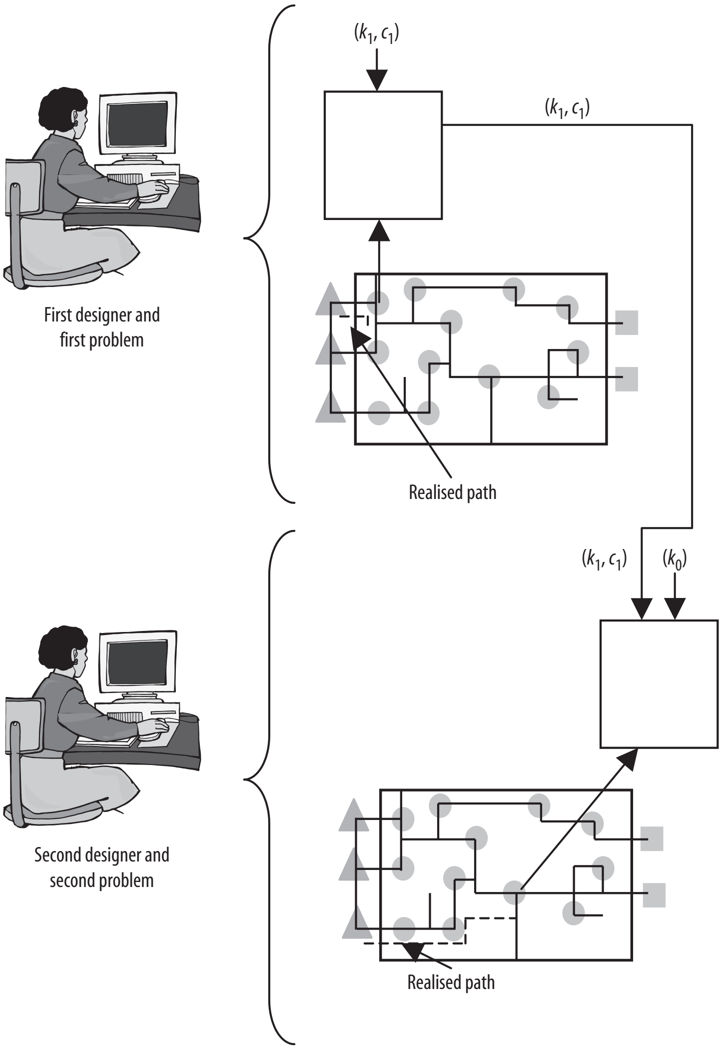

Figure 2.7 Coordination between two designers.

to the second sub-problem are not Pareto-optimal. Similar dependencies exist between the second Pareto-optimal set and the corresponding points in the first sub-problem. If we first solve the first sub-problem then we will have a limited choice in solving the second one. If we solve the second sub-problem first, then we will have the opposite situation. In any case there is a conflict between our two sub-problems, and they should be solved in a rational way. Probably we will have to make a compromise between these two sub-problems. We can do this if we cooperate while selecting the optimal solutions. For instance we should try to understand the consequences of selecting particular decision variables for both problems and try to satisfy both points of view in a certain limited way. The selection of common decision variables will be known as coordination, and the common work to find compromises will be known as cooperation.

Designers usually work in teams. This means that people have to coordinate their activities and that they can cooperate while solving their problems. We can easily evolve our example into a case for two designers. Each designer assumes responsibility for his respective problem. Then they solve their problems separately and have different solutions in the decision space. There would then be no coordination. However, they could work with one dominating the other. We have created a privileged situation which would allow the senior designer to solve his problem first and thereby dictate his decision variables to the second designer. These situations are presented in Figure 2.7. The two designers could also cooperate and create a common compromise. This could also be done at a distance (Figure 2.8).

The designers' work is based on knowledge. Design knowledge can be modified and can reflect progress in a domain. This knowledge can be used by various people. Most people employ some archetypes when applying the knowledge. There are even sets of different archetypes. Moreover, archetypes are domain specific. They are often created by teams and used by a wider community. However, there are also archetypes which are applied only by a single designer. Anyway, both cases cause problems because for successful communication among designers and to fully understand designers' work, it is important that all people involved use the same, or at least similar, archetypes.

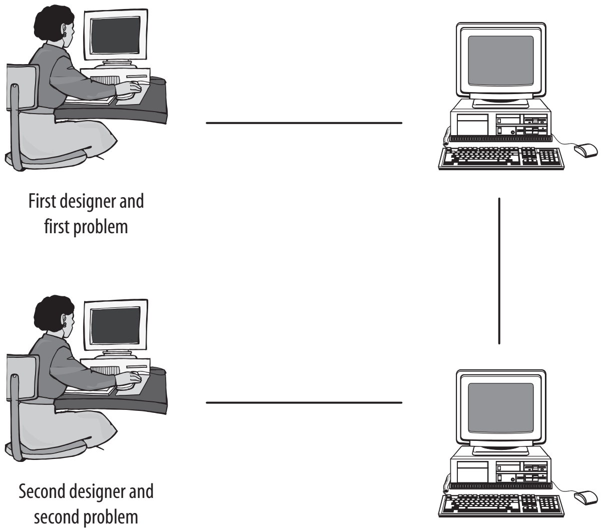

Figure 2.8 Cooperation at a distance.

2 The Nature of the Personal and the Team-based Design Process

Every design process is initiated by a specific need. This process normally starts with some ideas. Gradually the designer develops a basic concept which meets the need. He analyses and evaluates developed ideas. He has to create and be precise with his design details. This multistage activity is called the design process. Questions relating to this process are [5, 35, 50, 51, 62, 65, 68, 101, 106, 112, 113]:

- How do individual designers work?
- How do concepts appear?
- How is a concept developed?
- What are the sources of inspiration?
- How are different interactions between connected sub-problems achieved?
- How does the designer handle design process iterations?

As was found by research, designers often do mental modelling. They exploit their imagination and work with pictures in their minds. Then they try to figure out characteristics of the problems. Often, while explaining their task to other people, designers begin to understand the matter themselves. It becomes more clear to them and they find new ideas.

With more complicated problems some designers try to sketch their ideas on paper or use a CAD system. Others build physical models and test their concepts at once in "reality". The third group are quick thinkers who are immediately able to express their ideas on how to handle the problem. Others have to speak with other people. Finally, all the different ways of approaching a project help the designers to understand the main problem of the task and clarify its characteristics.

During this initial stage of the process the designers look for new information and try to form associations with what they already know. Everything is done with the intention of finding a solution to their problem. They do some mental inference.

The designers do their analysis with the help of a multitude of models and tools. The models which are considered could exist only in the designers' minds or be expressed in a more formal way. The designers build the so-called formal models often by using formal methods and formal software.

The human ability to build models and test them is still the key aspect of designing. Specific knowledge is connected with every technique of modelling and analysis. This knowledge decides what analysis can be done, what goals can be achieved and how the design process can look in a particular case.

The sequence of problems considered in the design process reflects the design history and can be a good source of information for solving particular problems. It may also be a source of available plans already applied in a design process.

The knowledge stored by designers is continuously modified. Each project analysis can give impulses for a new articulation or modification of a knowledge chunk.

Designers exploit their own memory for storing different kinds of knowledge or for the evaluation of other knowledge sources by referring to notes and schemes.

Very interesting results with the interdisciplinary empirical studies of engineering design can be found in [5, 22, 35, 50, 51, 67, 100, 106]. The research presented was done in industrial design offices and university laboratories over many years. One of the goals of this research was to answer the following questions from the perspective of our times:

- What patterns of thought do designers use while problem solving?
- What is the influence of formal methodologies?

The results obtained are multidimensional. Details of different design stages, different models, different tools, the influence of computer tools and the way they are used are considered. Very informative are the results of the comparison between designers who are only practitioners and designers who have a methodological education. Along with this are extremely interesting comments about the form of information which is applied during the design process and the way this information is transformed. The observed relationships between individual and team work in real cases are significant, for instance [67]: "in design processes individual work dominates to an extent $>70\%$ compared to $<30\%$ of teamwork."

For us, most significant is the variety of ways that designers do their job at each stage (individually or in a team). We can notice a strong influence of subjective and personal factors. If in addition we think of the knowledge behind every design decision, we see clearly the importance of these personal and subjective aspects; most of the design knowledge has such roots. Environmental conditions can also play a significant role.

If we want to consider a particular design process realised by a particular designer we not only have to understand his actual knowledge-intensive activities, but also some background knowledge concerning his professional experience. In the case of team work this aspect often becomes even more important.

The development of computer technologies has changed the shape and the range of analysis carried out during the design process. It allows classic approaches to be exploited to a wider extent. New methods have been developed which were originally invented as a computer approach. The problem of interaction between man and the computer implementation of a particular method has become very important. The interaction between the designer and the design problem can be considered on different levels. The levels are set on the basis of cooperation between man and computer. However, this classification has a very strong influence on the particular level and the knowledge structure. When we speak with designers they mostly use the following levels:

- Designer–domain problem (e.g., domain knowledge for the class of problems in machine design or mechanics). This is the highest and the most abstract level, which is very well synthesised. The knowledge presented in this context is very valuable. We can observe an articulated knowledge structure, its hierarchy

and its dynamic historical aspect. Hereby the designers use analogies and metaphors while explaining. Listening to them, we can almost sense (if we have enough imagination) how two surfaces cooperate in a joint or how one toothed wheel fits into a second one, for example.
- Designer-methods of particular domains (methods which belong to a particular domain and have an acting function). They support the process of achieving valuable solutions. Most of the designers who achieved the first level did their work exploiting relatively wide experience with some models and methods. Each of their cases solved in practice has a knowledge-intensive background. They can present practical knowledge on how to solve a particular problem by giving the evaluation of the whole approach. Additionally they compare this approach with other approaches, indicating their advantages and disadvantages. We can learn how the approach was developed over some years.
- Designer-methods of a particular domain in a programmed form. Today many of the engineering problems are solved with the help of computers. Consequently behind the designers' decisions stand processes or other steps realised by computer systems. This is connected with very practical knowledge assisting in solving design problems with a particular computer code.
- Designer-computer systems, including methods of a particular domain in programmed form. Rarely does a designer use only one single computer tool. Often a variety of tools are used as a part of a larger task. This can be thought of as the building of a code of codes. One of the main technical problems is its integration. However, at the moment, most important is the knowledge of how and why new tasks are created, which is obviously the consequence of new integration ideas.

From a certain stage, most of the design problems are solved with the help of computer systems which allow different computer models of design products to be built. The designer's work is to extract important artefacts which can be formed from his mental models. Then he must "squeeze" them into the frames of existing computer systems.

Later he has to follow the design process and do the same with different analysis, considerations and details; and at every step he has to consider what parts of his mental work can be placed in the formally developed models and descriptions. This is a situation we are always confronted with, irrespective of whether we use computer tools or not. One has more freedom in thought than in action. From this we gather that a design process developed by a designer is richer than its formal representation can ever be.

Let us take an example from machine dynamics.

Example 2.1

The development of computer technologies has a strong influence on the range of analysis in machine dynamics [12, 72, 78, 90]. Many problems previously regarded as complicated have become routine.

However, some classes of problem have been left unchanged by this development. Up to now it is still difficult to store the knowledge of modelling and solving a particular problem. If somebody wants to solve a certain problem in machine dynamics (a particular phenomenon or product) he has to build (or select from earlier considered models) and examine several models. This process can be called problem learning (by the designer). In many cases it is a long and time-consuming process.

The modelling of a car dynamics model means a lengthy period of work for the designer. For the modelling of a specific multibody system, for example, it is necessary to describe a system of bodies, their connections, their parameters and their external forces.

A real car dynamics problem will serve as our example: the stabilising moment of the steering wheel. We started analysing our problem by reviewing relevant literature. We found several descriptions of this problem. There are also some theoretical models and mathematical formulas. They present a part of the abstract knowledge, which gives a general overview of existing problems. However, in the literature there are hardly any examples of described models. It is very difficult to find out which model could be used in our specific situation. All described models are similar to each other as far as their complexity is concerned. So to put in order and complete these pieces of information we arranged meetings with an expert from the domain [12, 78, 90]. The expert has been dealing with simulation models of cars for more than 20 years, therefore he has extensive practice and theoretical knowledge. We obtained from him information about the relevant cases resulting from negotiations with clients, decisions regarding constructions of a new model and the adoption of a new problem to already existing solutions. We were particularly interested in the way he collected data, searched for missing data, and finally assessed the achieved results.

We have noticed that the expert at the beginning of each thread often refers to one of the previous cases. Then he establishes the procedure for the actual case and tries to generalise it. This is how a linear description of problem solving arises. After the expert has presented several cases we notice that there are common points in the set of linear descriptions. We connect these points and we notice that the output reminds us of a maze model. Figure 2.1 shows us how to proceed with the problem. The diagram presents the way of adapting the problem to existing models and the possibilities of building a new model.

The expert divided the problem into several subgroups. These subgroups distinguish the way the problem is perceived: how deeply one wants to analyse it, which situations are taken into consideration, if the driver's point of view is important in a particular case, or if the research results are to be used in court. When the problem is classified, it is necessary to find out the purpose of the research, what kind of data can be delivered, and the influence of geometry relationships on the final results. Finally, it is important to know who performs the research because some of the developed models are of an enormous value and cannot be disclosed. It should also be remembered that time and financial resources allocated to a project are of great importance. At the end

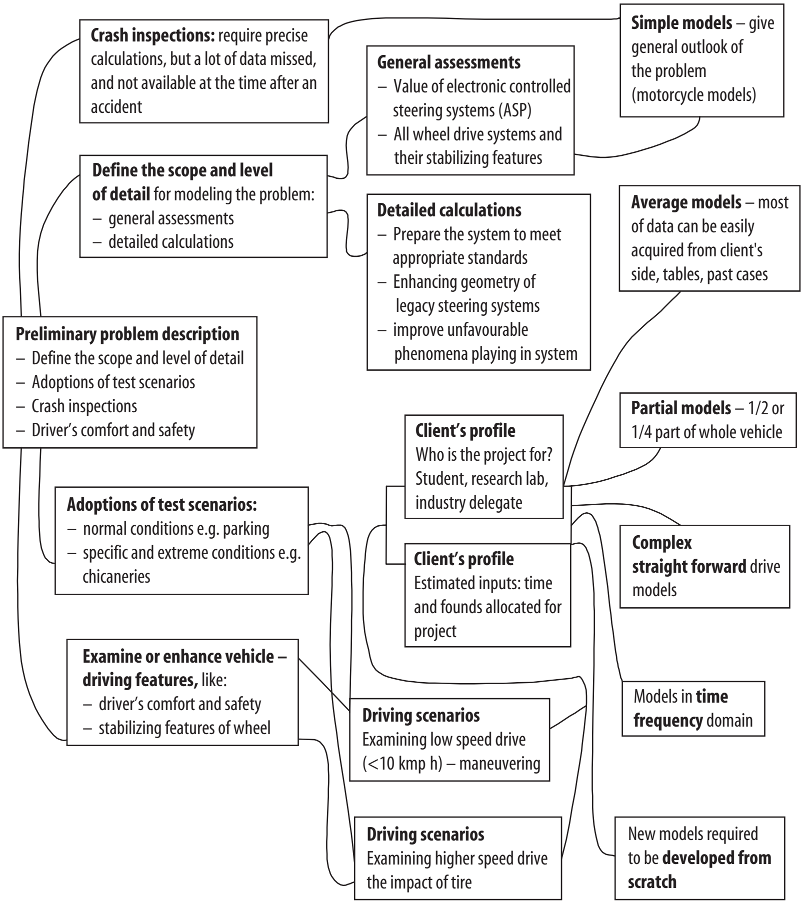

Figure 2.1 Expert's plan for solving car dynamics problem [78].

we can find out which of the existing models could be used in a particular situation, or if the expert would be interested in building a new one.

The results of our research can be described with the following characteristics. The number of degrees of freedom (if referring to multibody systems dynamics) is one of the most significant parameters. In real industrial cases it can amount to a few hundred and result in a multitude of models and analysis. The overall process of analysis can take several months. The designer formulates many rules in his mind and tries to explain the examined phenomena. Parallel to this he validates this knowledge, creates new or better rules and draws final conclusions. For this he uses written notes. At the same time the designer tries to improve his modelling, his methods of analysis and his parameters, and observes all the side-effects. All together it provides an immense field for searching.

In the above example, we presented the way human designers do their work; in a knowledge context and as individuals. The selected problem can be regarded as a specific design task realised by a single designer. Real design tasks consist of several sub-tasks. In his work, a designer does not only try to build the structures of his sub-tasks: parallel to this he also tries to optimise particular problems.

So while he is creating a path of sub-tasks (which reflects the core of building the problem structure) the designer at the same time is trying to select the best parameters for his solutions. In the end he can create a whole sequence of problems belonging to the category of optimisation problems. With every sub-task a multi-criteria optimisation problem created by the designer can be connected by selecting decision variables, constraints and criteria functions. The sequence of optimisation problems – accompanying a path of sub-tasks – can be mutually interacted with via decision variables, constraints or criteria.

However, optimisation problems of different sub-tasks can interfere. We want to clarify this problem by means of a simple example [64, 72].

Example 2.2

Let us assume that our designer has to consider the problem of moving a car with constant velocity and that he has to estimate the quality of the suspension [63, 72, 97]. He builds his first sub-task – a simple dynamic model – linear with two degrees of freedom (Figure 2.2). The equations of motion are

$$\begin{aligned} m_1\ddot{y}_1 + k_1(y_1 - y_2) + c_1(\dot{y}_1 - \dot{y}_2) = 0, \\ m_2\ddot{y}_2 + k_1(y_2 - y_1) + c_1(\dot{y}_2 - \dot{y}_1) + k_2(y_2 - q) + c_2(\dot{y}_2 - \dot{q}) = 0, \end{aligned} \tag{2.1}$$

where:

- m_1, m_2 are the sprung and unsprung masses;
- k_1, k_2 are the stiffnesses of the suspension and the tyres;
- c_1, c_2 are the damping coefficients of the suspension and the tyres;
- y_1, y_2 are the displacements of the sprung and unsprung masses;
- q is the kinematic excitation (road roughness).

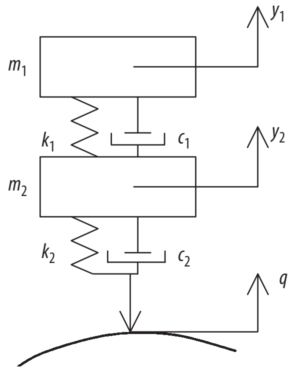

Figure 2.2 Dynamic model of car.

The designer assumed that the excitation is modelled as a stationary stochastic process with zero mean value and spectral density $S(v)$. The spectral density corresponded to the asphalt road and the speed of the car $v = 18$ m/s.

Then the designer selected a set of decision variables (stiffness and damping coefficient of the suspension). The feasible domain is defined in the following way:

$$\Phi_1 = \{(k_1, c_1) : k_{1\min} \le k_1 \le k_{1\max}\,;\ c_{1\min} \le c_1 \le c_{1\max})\}. \tag{2.2}$$

The designer selected two objective functions:

Q_1, the variance of differences between the displacements of the sprung and unsprung masses.

Q_2, the variance of the sprung mass acceleration.

The designer did calculations and obtained results. In Figures 2.3 and 2.4 we have the feasible domain together with the objective space

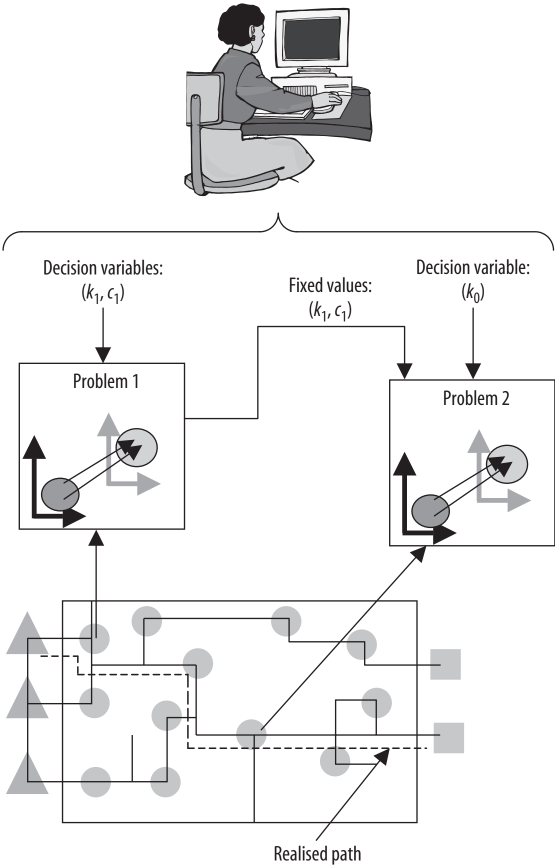

Figure 2.3 Optimisation problem together with maze model.

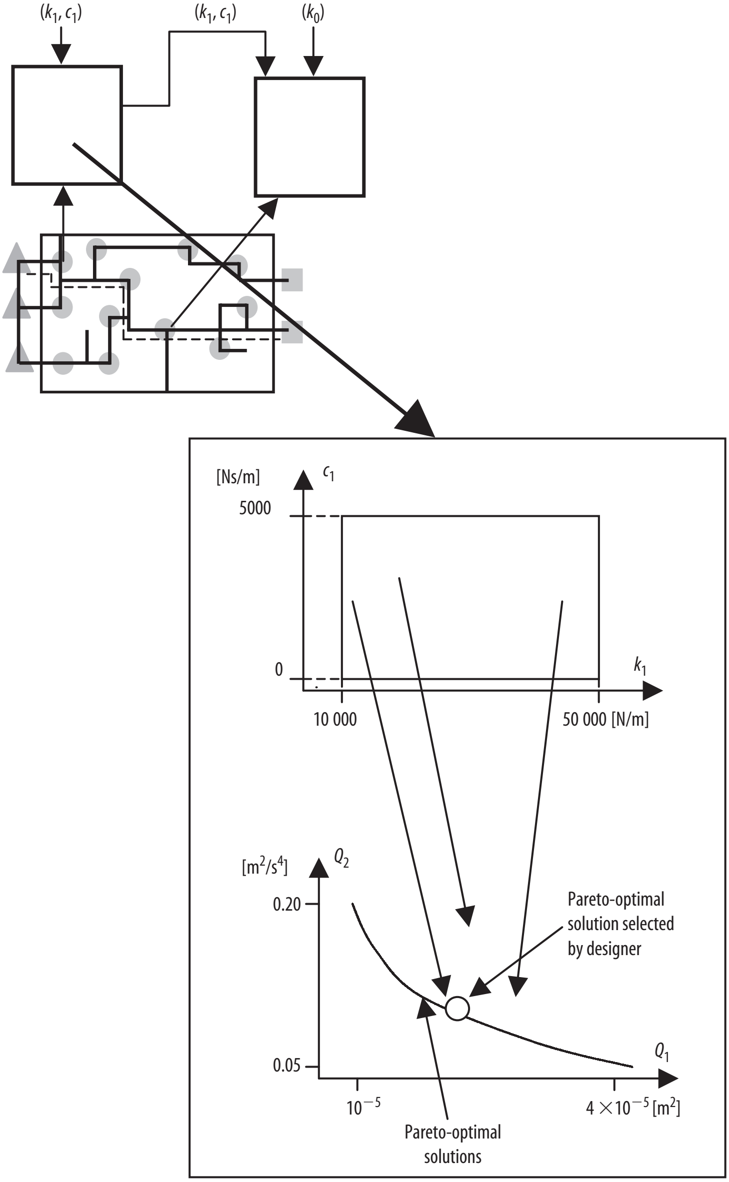

Figure 2.4 Results of first sub-problem.

with final results. As is visible in the objective space we obtain a Pareto-optimal set. This means that the points belonging to this set cannot be improved. After that the designer selected one of the points belonging to the Pareto-optimal solutions.

Later the designer started to consider the next dynamic problem concerning the respective car. He built a model which was suitable for examining how the same car performs when going over bumps in the road. Again he built equations of motion:

$$\begin{aligned} m_1\ddot{y}_1 + F + c_1(\dot{y}_1 - \dot{y}_2) &= 0, \\ m_2\ddot{y}_2 - F + c_1(\dot{y}_2 - \dot{y}_1) + k_2(y_2 - q) + c_2(\dot{y}_2 - \dot{q}) &= 0. \end{aligned} \tag{2.3}$$

The physical parameters are as in the previous model.

The elasticity force is a function of the spring deflection. The force has the following form:

$$F = \begin{cases} k_0(y_1 - y_2) + (k_0 - k_1)a & \text{for } (y_1 - y_2) \le -a, \\ k_1(y_1 - y_2) & \text{for } |y_1 - y_2| \le a, \\ k_0(y_1 - y_2) + (k_1 - k_0)a & \text{for } (y_1 - y_2) \ge a. \end{cases} \tag{2.4}$$

In this case the excitation was modelled as a single harmonic wave (H – height, D – wavelength, x – horizontal coordinate):

$$q(x) = \begin{cases} \pm\dfrac{H}{2}\left(1 - \cos\dfrac{2\pi}{D}x\right) & \text{for } x \in [0,D], \\ 0 & \text{for } x \notin [0,D]. \end{cases} \tag{2.5}$$

There were the following decision variables:

$$(k_1, k_0, c_1). \tag{2.6}$$

The feasible domain was defined as

$$\begin{aligned} \Phi_2 = \{(k_1, k_0, c_1) : k_{1\min} \le k_1 \le k_{1\max}\,; k_{0\min} \le k_0 \le k_{0\max}\,; \\ c_{1\min} \le c_1 \le c_{1\max}\} \end{aligned} \tag{2.7}$$

The objective functions were defined as

$$\min_{(k_1,k_0,c_1)\in\Phi_2} \left\{ \max_{t\in[0,T]} |y_1(t) - y_2(t)|,\ |\max_{t\in[0,T]} |\ddot{y}_1(t) \right\}. \tag{2.8}$$

Calculations were made for the fixed value of k_1, c_1 (from the first considered problem) and as a consequence, the designer obtained the results shown in Figure 2.5. These results were obtained when he considered problem 1 first and then problem 2. We assumed that the designer would solve both problems sequentially, according to their importance. It is also possible that the results which the designer acquired after solving the first problem enabled him to build and solve the next one. This thought process can be observed quite often.

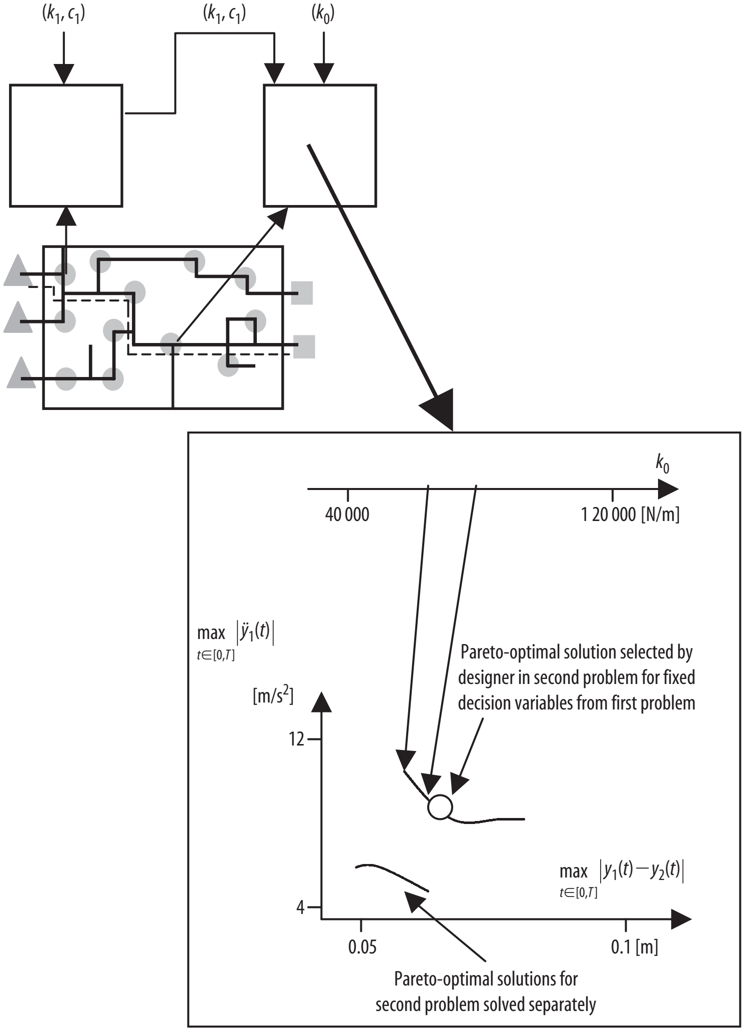

Figure 2.5 Results of second sub-problem.

The number of interconnected sub-problems can be higher than two. According to his knowledge the designer can consider various additional phenomena. Everything depends on the whole design problem and the goal of the design analysis. The sub-task structure of the path and the associated optimisation problems can be created dynamically by the designer.

However, the two interconnected problems presented above can also be considered in a different way. We can treat the two sub-problems as one global optimisation problem. In this case we can build a common feasible domain (Figure 2.6).

As presented in the figure, we have two objective spaces. Now we can observe that in both sub-problems two Pareto-optimal sets are achievable. However, if we analyse the points from the first Pareto-optimal set we will see that the points corresponding

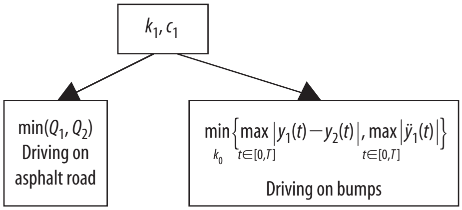

Figure 2.6 Structure of optimisation problem.

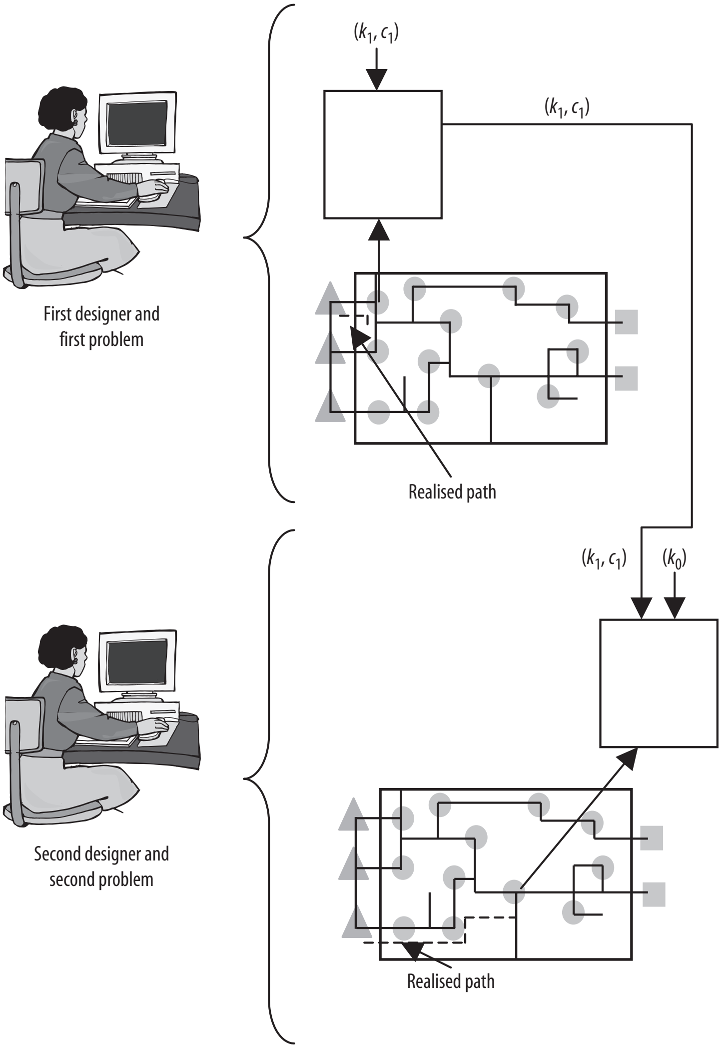

Figure 2.7 Coordination between two designers.

to the second sub-problem are not Pareto-optimal. Similar dependencies exist between the second Pareto-optimal set and the corresponding points in the first sub-problem. If we first solve the first sub-problem then we will have a limited choice in solving the second one. If we solve the second sub-problem first, then we will have the opposite situation. In any case there is a conflict between our two sub-problems, and they should be solved in a rational way. Probably we will have to make a compromise between these two sub-problems. We can do this if we cooperate while selecting the optimal solutions. For instance we should try to understand the consequences of selecting particular decision variables for both problems and try to satisfy both points of view in a certain limited way. The selection of common decision variables will be known as coordination, and the common work to find compromises will be known as cooperation.

Designers usually work in teams. This means that people have to coordinate their activities and that they can cooperate while solving their problems. We can easily evolve our example into a case for two designers. Each designer assumes responsibility for his respective problem. Then they solve their problems separately and have different solutions in the decision space. There would then be no coordination. However, they could work with one dominating the other. We have created a privileged situation which would allow the senior designer to solve his problem first and thereby dictate his decision variables to the second designer. These situations are presented in Figure 2.7. The two designers could also cooperate and create a common compromise. This could also be done at a distance (Figure 2.8).

The designers' work is based on knowledge. Design knowledge can be modified and can reflect progress in a domain. This knowledge can be used by various people. Most people employ some archetypes when applying the knowledge. There are even sets of different archetypes. Moreover, archetypes are domain specific. They are often created by teams and used by a wider community. However, there are also archetypes which are applied only by a single designer. Anyway, both cases cause problems because for successful communication among designers and to fully understand designers' work, it is important that all people involved use the same, or at least similar, archetypes.

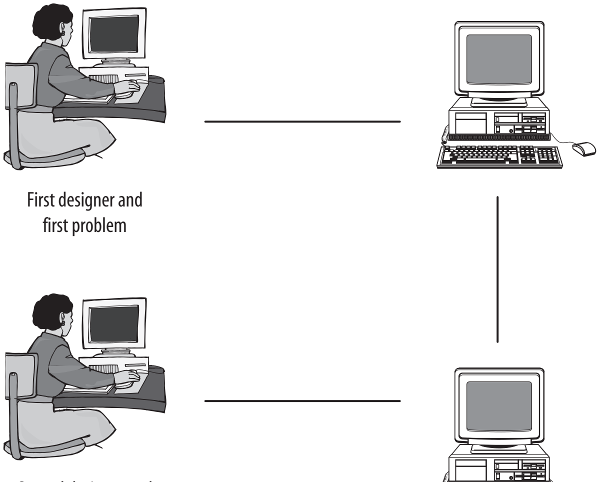

Figure 2.8 Cooperation at a distance.