Mathematical Application Projects for Mechanical Engineers - Concept, Guidelines and Examples

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***Abstract**: In this article, we present the concept of mathematical application projects as a means to enhance the capabilities of engineering students to use mathematics for solving problems in larger projects as well as to communicate and present mathematical content. As opposed to many case studies, we concentrate on stating criteria and project classes from which instructors can build instances (i.e. specific projects). The main goal of this paper is to facilitate the definition of new „good" projects in a certain curricular setting.*

1. Introduction

Learning and training mathematical concepts and algorithms in engineering departments of German Universities of Applied Sciences ("Fachhochschulen") usually consists of a sequence of "small steps" with "small-sized" assignments. This is necessary in order to gain familiarity without overloading students with too much complexity. But in the end, an engineer is required to use mathematics (models, software) for solving problems in larger projects as well as to communicate and present mathematical content. Without also learning this further step in mathematics education for engineers, mathematical knowledge often remains "inert" (Mandl), i.e. small chunks of knowledge are existing, but the capability of how to apply them for solving a problem is missing.

As a remedy, we introduced mathematical application projects in the third semester (Mathematics III) after students have learnt basic mathematical concepts and symbolic computation during semesters 1 and 2 in a mathematically coherent setting. The character and success of such projects heavily depends on the curricular embedding (mathematical and application field knowledge and capabilities of students) and on accompanying organizational and tutorial activities which we will describe in the next section.

In order to really achieve the objectives stated above and to avoid frustration, projects have to be defined very carefully. As [Ludwig] already observed, whereas articles containing descriptions of special projects or case studies are frequent (cf. for engineering mathematics: [Mustoe], [Westermann], [Challis], [Janetzko]), there is only few systematic work on projects. In order to pursue a more systematic approach, we present and explain several criteria which projects in our curricular setting should fulfill like openness, mathematical richness, interesting and meaningful application context, usability of mathematical software, modularity. In doing this, we take into account criteria stated by [Ludwig], [Reichel], [Ernsberger], and [Wilkinson], and we compare our type of projects with those described in literature.

Defining "good" projects according to these criteria is still a time-consuming task. We therefore tried to identify *classes* of application projects in mechanical engineering making definition of ever new projects easier by building *instances* of such classes. This way, individual projects can be defined such there is no copying of work of other groups in the same class or in former classes. As a worked example for a project belonging to one of the classes we then present the project "Motion function for the Hockenheim motodrom". Finally, we discuss our experience so far.

2. Curricular Embedding and Accompanying Activities

The mathematical part of the mechanical engineering curriculum at the Aalen University of Applied Sciences consists of three courses to be taken in semesters 1, 2, and 3, respectively. Mathematics I and II are lectured traditionally, including a written exam at the end. These courses contain the usual concepts of linear algebra and analysis. During the lectures, application modelling properties of mathematical concepts which are important in mechanical engineering are already emphasized. Moreover, an additional learning hypertext consisting of material on stress analysis and engineering mechanics as well as links to underlying mathematical concepts is offered (for a more detailed descrition cf. [Alpers, 1999]). Students get already an introduction to the computer algebra system Maple™, and a tutored assignment environment for mechanics is offered in Maple (cf. [Alpers, 2000]).

Placing projects in the third semester has the advantage that several application subjects are available making it possible to define meaningful application projects. Concepts of engineering mechanics (statics, kinematics, etc.), stress analysis, physics, and CAD are available. Mechanical configurations can be investigated in more depth mathematically. So far, the link between computation in Computer Algebra Systems (CAS) and geometrical modelling in CAD has been exploited frequently.

The theoretical content of Mathematics III consists essentially of numerical methods (numerical linear algebra, interpolation, approximation, differential equations) which often occur in application problems. These are taught at the beginning of the semester (weeks 1-5) in 14 lectures such that students have enough time for applying them in project work afterwards. Students get full credit points for providing, documenting and presenting a project solution. Guidelines for writing the documents and for preparing a presentation are given orally and as hand-out (cf. [Edwards] as a guide for this). There is no longer a written exam.

There are teams of up to four students working cooperatively on one project thus fostering communication capabilities regarding mathematical concepts. Since each group works on a different project, we avoid that one group works out a solution whereas others simply copy it.

Students are expected to work approximately 20 hours each on the project such that the overall effort needed for providing a solution should not exceed 80 hours per project. This gives a rough estimate on the size of a project. Formerly, students needed this time to work on assignments and for exam preparation, so there is no additional load on the students.

All projects defined so far involve the usage of computer algebra for "easy" modelling and computation. Therefore, a short refreshing of Maple is offered and there is a student tutor helping with CAS problems. Many projects also contain modelling and production of numerical input files for a milling machine which is done using a CAD system. For larger groups, there is an additional student tutor for CAD usage, particularly for importing data computed in Maple into the CAD system. Note that before the semester starts the students have already taken a practical course on using a specific CAD system.

As far as possible, we also make use of the facilities (parts, machines) available in the departmental labs, e.g. measurement facilities, produced parts, milling machine. Moreover, we can use the central physics lab for setting up certain experiments.

The curricular setting in [Wilkinson] who follow a similar approach introducing projects for electrical engineers, differs from ours since their projects are smaller and positioned within the first year of mathematical education. This makes our concept rather complementary than contrary to theirs.

3. Criteria for Project Definitions

As pointed out in the introduction, most of the articles on mathematical projects describe special projects or case studies. Besides this, [Ludwig] and [Reichel] are concerned with conceptual aspects, i.e. identification of properties and types of mathematical projects in school. Although our interest is in university projects rather than in school projects, their work is general enough to be of relevance. [Ludwig] provides the following classification:

- Projects can have a „magnetic mode“ or a „star mode“ depending on whether the project is centered around an application topic requiring („attracting“) several other areas or around a mathematical topic branching out into several applications. Our application projects clearly belong to the first class.
- Projects can have a „reflexion structure“ if they serve to get a deeper understanding of the meaning and applicability of already known mathematical topics; or they can have a „projection structure“ if they serve to develop and learn new mathematical concepts. Our projects have a reflection structure since the mathematical topics have been treated before.
- Projects have a „line mode“ if starting point and goal of the project are clearly prescribed (and maybe steps or hints on steps are also given, so pupils work „along the given line“); they have a „ray mode“ if only a main topic is given and pupils can work in different directions (rays). We try to reach a compromise in our projects: Although the project goal is given, clarification and discussion on meaning is often required as is the case in real engineering life. We will take this point into account in our list of criteria below.

[Reichel] make a distinction between extra-mathematically and intra-mathematically motivated projects. Our projects are centered around an application topic and hence clearly belong to the first class. On a different level, Reichel distinguishes between projects which

- serve to train a mathematical topic,
- develop a mathematical topic,
- make connections between different topics,
- work on given or experimental data,
- train ways of mathematical thinking, speaking and representation,
- prepare for a later major project.

In our projects, all of the above purposes except for the second one are of relevance where the diploma thesis can be considered as the major project at the end of the study course.

[Ernsberger] is concerned with interdisciplinary projects during the first period of study in mechanical engineering. He states the following criteria such projects should fulfil:

- problems should be solvable within the given timeframe
- there should be at least two solution alternatives
- solutions should require the usage of many topics taught in foundational classes
- projects should not require too much knowledge, they should leave room for students‘ interest.

Our own criteria are based on the above and on the curricular embedding outlined in the previous section:

a) **The project should be concerned with an - from a mechanical engineering point of view - interesting and meaningful application subject.**

   This means that an application which is important for mechanical engineers should provide the framework for the project. As mentioned above, [Reichel] calls such projects "extra-mathematically motivated projects". [Mustoe] emphasizes the importance to find the right balance between „meaningful“ and „too complex and difficult“.

   In mechanical engineering, mathematically "rich" topics include design of parts (curves, surfaces) or design of motion (motion curves, motion functions). In the next section we provide a set of application classes within which such topics can be identified. These projects offer a good opportunity to strengthen the connections to application classes like engineering mechanics or CAD.

b) **The project task should include a data acquisition phase, preferably by taking maesurements in the labs.**

   In order to enhance the connection with the real world, data which serve as input for mathematical procedures, should be acquired by real measurements in the labs which are available in a university environment. Another way could be data acquisition via the Internet for which we give an example below in section 5. [Challis] provides a good example for „beginning with data“.

c) **The project should require the application of important mathematical concepts and models.**
   Projects should need a rich mathematical background, i.e. mathematics should play an essential role for work on a project. To make this clearer, we give an example: If a project is concerned with surface construction (say, for a part of an automobile) and the task can be achieved simply by using surface constructions available in a CAD program where no mathematical understanding is required, this would not constitute a real mathematical application project. If, on the opposite, mathematical construction of a Bezier or a spline surface and experimentation is an essential part of the project, the project would fulfill this criterion.

d) **The project should require the application of mathematical software like CAS or numerical programs.**
   In their practical life, engineers will often use mathematical concepts and models within mathematical programs, which may be symbolical (computer algebra) or numerical. Therefore, it makes sense to let engineering students apply mathematical concepts and set up mathematical models using this kind of software. The software also makes it possible to handle realistic application problems which could not be dealt with using paper and pencil.

e) **The problem description should be open, it should not be too prescriptive wrt. the way of completion.**
   Whereas the usual "small" assignments provide a clear "work order" and mostly serve to exercise one concept in order to gain familiarity, a project task should not describe the way how to solve the problem. It is just the task of the project group, first to clarify the task (often corresponding with tutors including the author) as is usually the case in real life: First clarify with your customer what the problem really is all about, and then think about steps, methods or models to tackle it.

f) **The effort necessary to achieve satisfying results must not be too large (time-adequacy).**
   As mentioned in the previous sections, students are assumed to work on the project for about 20 hours each. It must be possible to get to reasonable results within this timeframe. If more is required, there is the danger that students do not spend enough time on other subjects (Mathematics III has 2 hours out of 30 in the third semester). On the other hand, there should be enough work for 3 to 4 team members.

g) **The project task should be modular such that subtasks can be delegated to team members.**
   It is the intention of team work on projects that project teams think about the neccessary work to be done and set up a work plan cooperatively. Project tasks should contain identifiable sub-parts which can be delegated to team members such that every team member makes a real contribution (and is forced to do so since the overall project is too much for just one or two team members to work on). This also makes it possible to include weaker students, e.g. when measurements or real production tasks in milling machines are part of the project.

It is certainly hard to define projects which fulfill all of the above criteria to full satisfaction. Ideas for projects can be collected from modelling books like [Edwards] or [Fowkes], or from CAS producers as in the [Maple Application Center]. Moreover, application colleagues can be a very valuable source since they have an immediate interest in the students working with

their models. Finally, machine parts, experiments, and production machines in the labs may also be quite inspiring.
In order to ease the work of the instructor defining projects we set up several classes of mathematical application projects in mechanical engineering which help in defining individual projects.

4. Classes of Application Projects

In the following we describe a set of application project classes and point out why instances fulfill (at least most of) the requirements listed in the previous section. Although the class-instance-metaphor has been chosen intentionally, one should admit that defining concrete project instances from the classes below is not as easy as declaring instances in object-oriented programming languages but still needs time and some anticipating thoughts on how students might work on the project. For space reasons, we only describe one class in more detail whereas for the others just the main topics are mentioned.

a) **Curve or surface reconstruction**

Projects belonging to this class are concerned with the geometric reconstruction of parts. Such a part might be the door of a car, a formed sheet metal, the clay model of a designer part or the cross section of knife in a slicing machine. Reconstruction of existing objects is an important part in mechanical design such that the first criterion mentioned above is certainly fulfilled. The first task in reconstruction consists of measuring points which then can be used for curve or surface construction. Here, the first interesting question for students is how to take measurements (usage of available measuring instruments, point density). This is also a subtask where theoretically weaker students can do more practical work. The mathematical subjects which are needed are interpolation or approximation (preferably with splines or Bezier curves), and curves and surfaces in parameter representation which are certainly important in engineering applications. It is not possible to do the necessary calculations by hand, so the application of mathematical software is required.

As to the fifth criterion (openness), there are different degrees of openness possible here: One could simply leave it to the students which mathematical concept to use, or one could be a bit more prescriptive. This is also connected with the sixth criterion (time-adequacy): If support for a certain kind of modelling (e.g. a spline-package in Maple) is available and this is the only way to complete work within a reasonable timeframe, one might as well include it in the project description. Using existing functions in a CAS environment still gives insight in the mathematical structure of the result (e.g. cubic polynomial pieces of a spline).

A further part of the project could be to move data from the mathematical programming environment (probably a CAS or numerical program) to CAD. One could, for example, restrict oneself to modelling just curves within the mathematical problem solving environment, transfer the data via a simple ASCII file interface to a CAD program and make more sophisticated constructions in CAD (construction of surfaces through curves). Starting with a mathematical program instead of immediately using CAD has the advantage that students really work mathematically and see the mathematical construct behind the geometrical objects which is not the case if they simply click on a button named "construct spline" within the CAD environment. In a last step students can even let the CAD system produce a data file for a milling machine (if available in the lab) and let the machine produce a (small) model. Whether or not this last step is performed can also depend on the capability of the students working on the project. Constructing real parts which can even be used in lab machines (e.g. guide blade of a turbine) seems to be a great incentive particularly for strong students.

Having different subtasks like measurement, mathematical construction with CAS, and geometric construction with CAD makes it easy and necessary (!) to delegate work to team members such that each member should be involved.

Now, if an instructor wants to set up a project of this class he/she first has to find a machine part (car door, connecting rod, etc.) with some freeform geometrical properties, and then has to decide what should be modelled (surface, cross-section etc.) taking into account time-adequacy. He/she should know what measurement facilities are avialable. These can be quite simple since a high precision reconstruction is not required. Besides this, the instructor should find out (once!) the mathematical modelling support in the CAS or other program (existing procedures). He/she should also get information on simple file interfaces and modelling capabilities of the CAD program used in his/her institution.

b) **Curve or surface synthesis**

Another important task in engineering is the design of new objects, e.g. constructing the surface of a windscreen or side mirror for an automobile, or a wing profile. Additionally, some practical constraints like maximum curvature should be part of the task description. Data acquisition here could consist of measuring boundary curves or bounding boxes. Mathematical concepts to be used are again splines or Bezier curves and surfaces and their properties like curvature. Openness can be assured by giving just constraints and possibly hints on quality criteria. Basic investigation is to be performed in a CAS environment, more sophisticated investigation of surface properties should then be done with CAD. Again, there are identifiable subtasks like measurements, CAS computation, CAD investigation, and possibly production.

c) **Motion curve and function synthesis**

The design of motion is another central task in engineering. This includes motion of machine parts like sliders in packaging machines as well as motion of "free" bodies like cars or autonomous robots. Time-adequate projects can be defined in this area if simplifications are used. This will be demonstrated in more detail in the next section where a model of the Hockenheim motodrom is constructed using arcs and line segments. The mathematical concepts required here are curves in parameter representation including arcs and line segments, spline curves and more general piecewise-defined functions. Within the framework of piecewise-defined functions topics like continuity and differentiability come up quite naturally. Moreover, function synthesis as opposed to analysis yields a wide field for open experimentation, and questions concerning quality criteria or optimality also show up.

Input data for such tasks might come from the Internet (course data) or from the lab where e.g. the motion path of a robot arm around an obstacle must be determined. One could also take a toy motodrom as starting point. Defining and experimenting with course and motion function requires a mathematical program (preferably CAS) since otherwise piecewise-defined functions can hardly be handled.

Modularity and hence the possibility to delegate tasks can be achieved by identifying the main tasks: data acquisition, curve modelling, function modelling. Moreover, this can be extended by animating the motion or by even realizing it in the lab, e.g. on a toy course.

d) **Comparison of simplified linear and exact non-linear models of mechanical configurations**

In engineering mechanics, there are often simplified linear models as well as exact-non-linear models of a configuration. Take for example the pendulum which can be modelled with a linear differential equation for small angles, the deflexionof a beam or the motion of a slider-crank mechanism. Literature on engineering mechanics or colleagues lecturing the subject can provide such examples. It is often possible to improve the approximation by using higher terms in the series representation. So, here is a wide field for investigating polynomial approximations and their range of validity. Besides this, the mathematical content might include the numerical solution of differential equations. Within the labs, such configurations are often available such that the validity of a simplified model can also be checked with real experimental data (e.g. bending a ruler).

Symbolic programs are useful particularly for series representation and work with polynomials of higher degree and also for comparison with real data as well as for computing numerical solutions of differential equations.

Subtasks here are real measurements, setting up linear and non-linear models, investigation of errors, finding a simplified model within a given error bound, animation or at least visualization. If a professional program for computing such configurations is available (e.g. for multibody dynamics) it is also interesting to compare results and see which model the program uses.

e) **Parameter-identification in mechanical configurations**

Many models contain parameters that are unknown and can only be approximated using experimentation data. This is, for example, often the case for spring or damping constants. Getting experimental data from such configurations (e.g. motion data) is the starting point for an approximation process using the least squares method. If no lab experiments are available, one can also - as a substitute - produce data (e.g. a curve on paper). The projects can be open in that students have to think about what kind of data (how much and when) they need and which class of model functions for approximation is adequate. The model including the unknown constants can easily be set up with CAS, and this also holds for computing sums of squares of differences, partial derivatives and solution of the resulting linear or non-linear system. For models where some of the unknown constants are non-linear, it is often possible to use first approximative values, apply linear least squares and use the output as starting vector for non-linear least squares. It is quite obvious that a rich set of mathematical concepts can be applied in this context. For some configurations it is easy to create an animation which can be done by one team member.

f) **Signal analysis**

Signal analysis is an important part in measuring theory. Often, „noise“ has to be removed in order to reconstruct the "real" behaviour of a machine part. Another important field of application is technical acoustics. The most prominent method of analysis is the construction of approximative fourier polynomials (DFT). For real mathematical investigation a mathematical program is required, not just an „fft-button“ of an application program. Signals can be produced by overlapping different sine functions including high-frequency noise or they can be recorded in the lab; the resulting *.wav-file can be converted into an ASCII sample file which then is to be investigated in a mathematics program (see also the [Maple Application Center] for handling *.wav-files in Maple). Students have to think about sampling rates, removal of frequencies, numerical storage of the unperturbed signal. Such signals can be made audible with freeware programs or specific Maple procedures. As to modularity, one can identify as sub-tasks: signal recording, production of numerical sample, DFT in CAS, investigation and modification of spectrum, production of output for an audio tool. As to openness, it is up to the students how to record, to experiment with sample rates, and to experiment with removal of frequencies.

g) **Motion or signal synthesis with fourier polynomials**

In cam design, the construction of periodic functions fulfilling certain requirements is necessary (e.g., prescription of points, line segments or other functional pieces necessary for guaranteeing synchronization). For this synthesis task, approximating fourier polynomials are used in order to avoid the occurrence of eigenfrequencies (only sine functions with frequency below the first eigenfrequency of the excited system are used). It is surprising for students how well even straight lines can be approximated with only few frequencies.

Another similar interesting field is the construction of audio signals with fourier synthesis.

h) **Synthesis of machine parts under certain constraints**
In the design of machine parts or small constructions which is the subject of an important lecture in mechanical engineering, often parameter variation, functional dependencies (where do I gain most?) and optimisation questions are interesting. Examples can be provided by the person lecturing the subject or can be found in books on machine elements.

i) **Means of curve, surface and volume construction in CAD programs**
CAD programs contain a variety of construction methods for geometric objects (offset curves and surfaces, rotation of curves, blending, sweeping etc., cf. [March]), and during the CAD lecture just the basic ones can be dealt with. Moreover, students hardly see what is "behind the button". In mathematical projects, some of these can be investigated in more detail where CAS is an adequate computational environment. Geometric objects computed in CAS can be imported in CAD and compared with the CAD construction.

j) **Approximative construction of parts with reduced modelling possibilities**
Some production machines can only work with a reduced set of geometrical objects: An older turning lathe, for example, can only deal with polygonial cross-sections, i.e. line segments, and the milling machine can only deal with line segments or arcs. So, an interesting question with a high potential for experimentation is how to approximate a given curve (polynomial, spline, etc.) by using the available objects.

k) **Construction of mathematical representations for interface definitions**
Standardized ASCII-file interfaces in CAD (like STEP-ISO 10303, VDA-FS by the German Association of Automotive Industry) enable the description of a lot of geometrical objects (lines, polynomial curves, spline curves etc.). Such objects can be computed in a CAS (or numerical) environment, written into a file adhering to the standard under consideration, and read into a CAD program. Here again, CAS and CAD plots can be compared.

5. Worked Example: Motion Function for Hockenheim Motodrom

The project description handed out to the student group had the following content:

Project: Hockenheim Motodrom
„Model the Hockenheim motodrom mathematically and construct a reasonable motion function taking into account realistic restrictions. Provide a simple animation with Maple.“

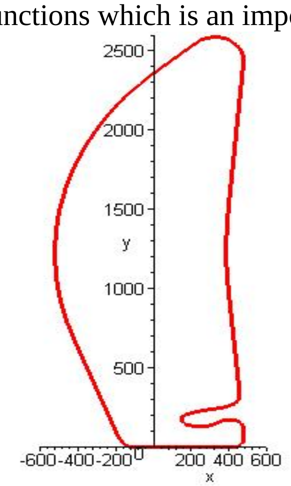
This project clearly belongs to class c) „Motion curve and function synthesis“ although the curve synthesis is not free since the Hockenheimring should be modelled. Students started with the data aqcuisition phase which mainly consisted of getting course and related data from Internet sites (here: www.hockenheimring.de). In particular, they retrieved a simple course model consisting of line segments and arcs (so width was not modelled which is reasonable for reducing complexity). They first used this data for reconstructing the course with a CAD system since they were already accustomed to constructing cross-sections using line segments and arcs. Using these objects in CAD and setting up a mathematical representation in CAS are quite different. For the latter, the mathematical concept to be used are curves in parameter representation. Students had to retrieve their knowledge on lines and arcs in parameter representation: line segments between two points are usually constructed with a parameter running from 0 to 1 and arcs by running through the angle section. In the next step, they had to construct a piecewise-defined curve with just one running parameter, so students had to think about re-parameterization. For later construction of a motion function and animation, arc-length parameterization is the most useful one but at this stage this is not necessary. The resulting curve with some simplifications (not all chicanes are modelled) is shown below.
For constructing a reasonable motion function, first realistic constraints had to be identified. These can also be found in the Internet. Students decided to use information on maximum velocity in curves (depending on the radius), maximum velocity of the car, and maximum positive and negative acceleration. They worked with a simple model where only full positive

or negative accelleration was allowed, and made use of their kinematics knowledge learnt in engineering mechanics. They constructed the function v(s) (velocity depending on distance) using constant accelleration a_0 which is in general given by $v(s) = \sqrt{(v_0{}^2 - 2a_0 s_0) + 2 \cdot a_0 \cdot s}$ (v_0 and s_0 are initial velocity and distance resp.). The challenge here is to construct the parts in such a way that accelleration is stopped early enough such that the maximum velocity allowed is not exceeded. So, students really had to „construct with functions“ even if the functions under consideration (square root and constant functions) are simple. The resulting function is shown below. The last step then was to compute the distance function s(t) from v(s) which is also treated in the engineering mechanics class. Here, first t(s) is computed using $t(s) = t_0 + \int_{s_0}^{s} \frac{d\bar{s}}{v(\bar{s})}$. This function is invertible since in Formula 1 going back is only reasonable if you ended up in the gravel but driver mistakes are not modelled here! Having the motion function s(t), one can compute the lap time. This is an important point for controlling whether or not the modelling and the simplifications are adequate since lap times are also given as empirical data. It turned out that the lap time of the constructed motion function was a few seconds better than the empirical lap times which is a satisfying result.

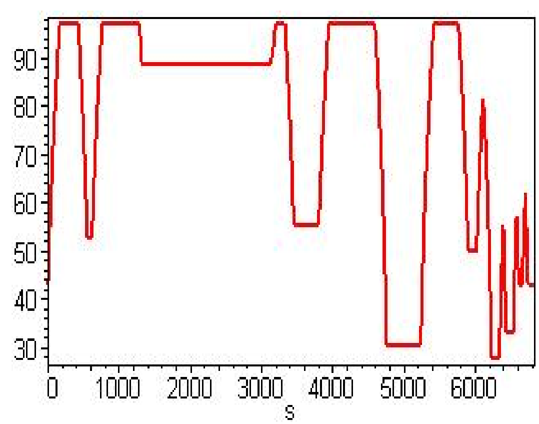
Finally, to get an optical representation and control, a Maple animation was set up by letting a small circle move around the course according to the motion function. Here, as well as for constructing the piecewise-defined course curve and motion function, the usage of a mathematics program, preferably a CAS, is inevitable.

Three students worked on the project, one using CAD modelling, one constructing the curve and the animation and the last one working on the motion function in CAS, so the delegation aspect was satisfactorily realized. Yet, students worked more than the envisaged 20 hours each, particularly on the CAS part.

Although the mathematics needed for this project is not particularly difficult, students realized how to apply it and got a much deeper understanding of parameterization and piecewise-defined functions which is an important topic in engineering modelling.



Hockenheim Motodrom



Motion function

6. Discussion and Conclusions

In the summer term 2000, there were 11 students working on 3 projects, in the winter term 2000/01 59 students working on 16 projects. In general, motivation was good to very high, only one group out of 16 did not manage to finish the project. A positive aspect of projects defined according to the criteria stated in section 3 is that students either really work on and are committed to such a project and then succeed (with help) or they will fail. So there is no „quick getting through“, avoiding the effect that students learn heavily one week before an exam just to forget it with the same speed afterwards.

The author as instructor had several meetings with project groups for clarification of tasks, mathematical content, how to proceed and split work, and discussion about reasonable project simplifications and restrictions. The author acted as „customer“ the students had to cooperate with and to satisfy somewhat resembling the real world of a practising engineer.
The reaction of students was in general positive but some complained about the workload, partially stemming from unequal distribution of work within groups, partially because the projects were rather challenging whereas small-sized assignments and exams were familiar and easier to handle. This applies particularly to weaker students who needed more help and hints, whereas stronger students rather appreciated the bigger challenge and often worked much more than required. But also the weaker students got a better understanding of applying mathematics and were content at the end when they managed to come to a result.
When setting up the project tasks for the summer term 2001 (9 projects) and the winter term 01/02 (20 projects), the criteria and classes outlined in sections 3 and 4 were both applied and further developped. Having made criteria clear and having a set of classes made the project definition considerably easier but this task is still time-consuming. The author intends to make a (growing) set of project class and instance descriptions available via the Internet. It would also be helpful to set up a common library of projects and project classes as was suggested by [Challis].

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