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Sustainable Development as an Integral Part of the Design and Synthesis Exercise in Aerospace Engineering*

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The BSc programme in Aerospace Engineering at Delft University of Technology (TU Delft), Delft, the Netherlands, concludes with a design and synthesis exercise in which a team of students has to design an aircraft, a spacecraft or a space mission. Sustainable Development (SD) forms an integral part of the exercise. This trains students in taking a sustainable approach in their future engineering practice. The learning objective is to familiarise students with sustainability, sustainable design strategies and sustainability analysis, as well as skills gained in applying the acquired knowledge in designing aircraft and spacecraft. In the first week of the exercise, students participate in a workshop designed to initiate the SD part of the assignment. The workshop teaches students some SD terminology and motivates them to integrate sustainable solutions into engineering. In the following weeks, the SD lecturer observes and supervises the design process. The article describes the incorporation of Sustainable Development in the exercise by means of a case study wherein students designed a solar powered aircraft that had to serve as a replacement of satellites. By flying continuously (year-round) without a pilot at a high altitude, it should be able to take over some of the major functions of satellites. Propulsion was to be delivered by solar energy alone. The propulsion system should be designed so that the system is capable of propelling the aircraft, both in summer and winter. The article concludes with results of the evaluation, which was performed at the end of the exercise, as well as new developments.

INTRODUCTION

Since 1998, all students at Delft University of Technology (TU Delft), Delft, the Netherlands, are trained in Sustainable Development (SD), which plays a role in both the BSc and the MSc programmes [1]. In the Bachelor programme at the Faculty of Aerospace Engineering, the course in Sustainable Development is integrated in the final exercise. In the Master programme, Sustainable Development is taught as a separate course for all students. Next to this, students are offered the opportunity to integrate Sustainable Development into their final thesis work, before taking additional training [2].

The BSc programme in Aerospace Engineering at TU Delft concludes with a design and synthesis exercise. In this design and synthesis exercise, a team of students has to design an aircraft, a spacecraft or a space mission. The design synthesis exercise consists of two parts, namely:

1. Design project;
2. Supporting short courses.

The supporting courses include:

- Project Management;
- Systems Engineering;
- Sustainable Development;
- Library Utilisation Course;
- Presentation Techniques.

During the exercise, students are given the opportunity to obtain *design* experience in the design project. This means the complete design process, from drawing up a programme of demands (in this case specifications) to the design presentation, will be covered in

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a structured and iterative manner. This covers all familiar aspects that are typical of such a process, like making choices, taking into account conflicting demands while optimising, etc. Obtaining design experience also means that an iterative process is completed where non-optimal decisions are corrected in order to meet the specifications drawn up at the start of the exercise.

SUSTAINABLE DEVELOPMENT AT TU DELFT

Around 1970, the life of a person who wanted to save the environment was so much simpler than it is these days. Pollution was a clear problem that could be seen properly as black exhaust emissions, litter everywhere, nuclear waste, etc. The industrial revolution had caused a lot of dirt that needed to be cleaned up.

During these years, environmental issues were seen as isolated problems that needed to be tackled separately. In 1970, the first Dutch environmental pollution law was established for the protection of surface water; many similar laws followed and a system of *pollution* permits was introduced.

Yet after all the actions taken and laws made, companies were overwhelmed and confused by measures that were sometimes even conflicting. In the end, these end-of-pipe measures seem to help some, but not sufficiently. It did not really solve the problem of diminishing biodiversity, global warming, the depletion of natural resources, population growth, etc. The problem was – and still is – much more complicated than once thought.

In 1987, new thoughts were put on the social agenda by the Brundtland committee via the report, *Our Common Future*. This United Nations (UN) report stressed the relationship between economical development and the environment, but also other important elements like political freedom and social justice. This committee introduced the following definition for Sustainable Development as a common goal. This definition is used as a starting point for discussions around Sustainable Development:

> *Sustainable Development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

Engineers have an important role and responsibility in achieving Sustainable Development by utilising new technologies, and by being key persons in the design and development of many products and systems.

Since 1998, all students at Delft University of Technology are required to receive some training in Sustainable Development. Students should meet the following objectives after having taken the training:

- Have the knowledge of the concept and terminology of Sustainable Development.
- Can place their technological knowledge and skills in the context of a broad social challenge.
- Understand how technical sub-systems are related and how social aspects influence the performance of a technique.
- Recognise the cause of sustainability problems within a broader framework than on the level of sub-systems, and are able to look further than the borders of their knowledge area when looking for structural solutions.
- Have attained skills to work together with other technological and non-technological disciplines in designing and maintaining technical systems and communicate properly about sustainability issues with stakeholders.
- Can identify strategies to solve sustainability problems and recognise the effects of solutions in the longer term at larger scales (geographically) and at other system levels (technical and organisational).

OBJECTIVES AND SET-UP OF THE DESIGN AND SYNTHESIS EXERCISE

The objective of the design and synthesis exercise is to enhance certain skills. These are skills in the following fields:

- Design;
- Knowledge application;
- Communication (including discussion, presentation and reporting);
- Teamwork;
- Sustainable Development (SD).

The duration of the exercise covers 9-11 calendar weeks, depending on the holiday period in that part of the year. Students are expected to put in a minimum (and preferably a maximum) of 40 hours of work per week into the exercise. There is no room for other (study) activities. The project introduction is in March and attendance is mandatory.

During this introduction, students are given the opportunity to express their interest in specific projects. The exercise ends with a symposium in which all project teams present their results before a jury, their fellow students and their parents. Examples of design projects over the last years include:

- Acoustically and Environmentally Friendly Aircraft (AEFA);
- Unmanned aircraft for delivery of emergency relief;
- Solar powered aircraft;
- Lunar mission;
- Solar power satellite system;
- Reno racer;
- Tsunami detection and warning system;
- Tailplane design [3].

SUSTAINABLE DEVELOPMENT IN THE DESIGN AND SYNTHESIS EXERCISE

Sustainable Development (SD) forms an integral part of the exercise. This trains students in taking a sustainable approach in their future engineering career. The learning objective is to familiarise students with sustainability, sustainable design strategies and sustainability analysis, as well as skills gained in applying the acquired knowledge in designing aircraft and spacecraft. This is important because sustainability is not considered a hard engineering discipline and, therefore, often tends to be forgotten. In real life, society increasingly demands sustainable designs.

In order to incorporate Sustainable Development in the design specification, the SD lecturer contacts the coach of the design team in an early stage. They discuss the design assignment and the possibilities to include Sustainable Development in a natural way as much as possible.

Set-up

In the first week of the exercise, students participate in a workshop designed to initiate the SD assignment. The workshop teaches students some SD terminology and motivates them to integrate sustainable solutions into their engineering work. At the first group meeting, the SD assignment is handed out together with the overall group assignment. The first part of the SD assignment is discussed and students can start working on the assignment. During this workshop, student-assistants are present in order to help groups or individuals.

In the subsequent weeks, the SD lecturer observes and supervises the assignment. In order to ensure smooth progress, the following review points (by appointment) have been set:

- Week 2: Review of the current status by means of an interim report that covers the first part of the assignment (ie the actor/trend analysis).
- Week 8: Presentation of Sustainable Development solutions in the overall assignment.
- Week 11: Integration of the Sustainable Development solutions into the final report.

So as to ensure decent supervision, there must be at least one meeting per week between the groups and the SD lecturer set up between the workshop and review points as stated above. This meeting can take place by e-mail or during open office hours. The SD lecturer can always be reached via e-mail and is to be present at least three half days for open office hours.

Deliverables

During the design and synthesis exercise, the following deliverables are compulsory for SD:

- An interim report covering the first part of the SD assignment (ie actor/trend analysis), which has to be handed in at the end of Week 2.
- A presentation that focuses on SD and covers all matters concerning SD in the project; this takes place in Week 8.
- The integration of SD solutions in the final report. This has to be handed in as a hard copy at the end of the design and synthesis exercise.

CASE STUDY: DESIGN OF A HIGH ALTITUDE LONG ENDURANCE UNINHABITED SOLAR POWERED AIRCRAFT

This section describes the design of *Phoinix*, a High Altitude Long Endurance (HALE) platform: an air vehicle that is designed to operate at a high altitude in the Earth's atmosphere for long periods (over six months) carrying a certain payload [4]. This design project illustrates nicely the design and synthesis exercise and the incorporation of Sustainable Development in the design.

The group of nine students initially designed several concepts fulfilling the specifications. Figures 1a to 1c illustrate three of the concepts developed.

In a trade-off analysis, the best concept was chosen. All aspects of the design are discussed during such a trade-off study, some of which is illustrated here to show the choices the team made for their final design.

Power Considerations

Unlike conventional airplanes, solar powered aircraft do not have a constant energy supply. Apart from the

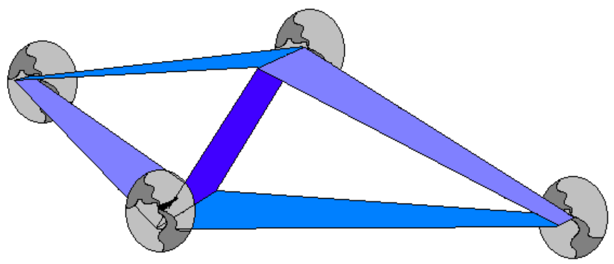

Figure 1a: *Biplane* concept.

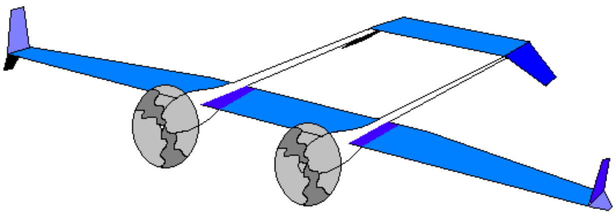

Figure 1b: *Conventional* concept.

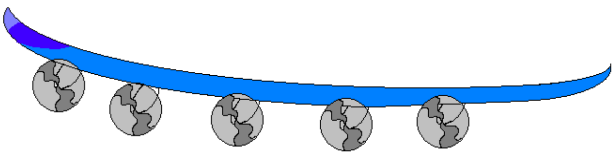

Figure 1c: *Flying wing* concept.

fact that the sun does not shine at night, the amount of available power also depends on the angle between the normal vector on the solar panels and the direction of the sunbeam. The intensity of the sunlight is also an important aspect. Figure 2 displays a contour plot of available power for each day of the year at each altitude

Since the sun's position varies continuously during

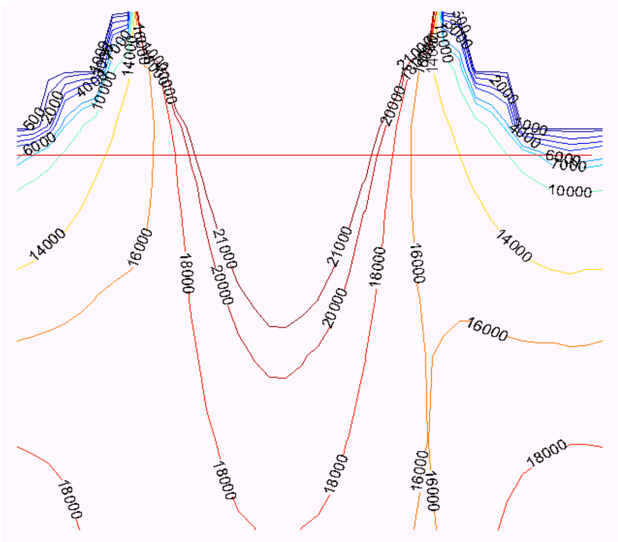

Figure 2: Contour plot of available power [W] for each day of the year (x-axis) at each altitude (y-axis).

the day, the platform was equipped with rotating solar panels for the detailed design phase. These *sun tracking* panels are mounted on the tail booms and their angular position is automatically adjusted to retain the optimal (largest) angle of incidence and solar flux of the solar radiation vector on the solar arrays. When these tracking panels are installed, energy collection is most efficient and aircraft dimensions reduce to normal values. Figure 3 shows the layout of the concept, with the sun-tracking solar panels mounted on the tail booms.

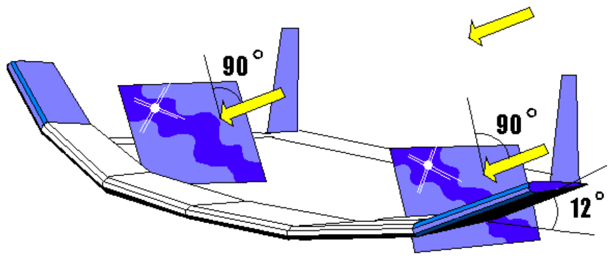

Figure 3: Layout of the concept, with the solar panels attached to the tail booms.

In order to secure propulsion and payload power at nighttime, daytime excess power has to be stored. The only way to store these amounts of energy with an acceptable storage system weight is the use of fuel cells. Today's fuel cell technology allows energy storage and expenditure with a total efficiency of up to 67%.

Structural Considerations

Flying on solar power requires a careful balance of energy collected and energy expended over each day. When an aircraft with a certain mass has to stay airborne for long periods of time and carry a payload, a large amount of energy is required. The slightest extra mass carried has a very high price in energy consumption because it has to fight against gravity every hour of the day. Seeing that the amount of required power has to be minimised for year-round service, with regards to the structure, all measures have to be taken to win every possible kilogram on the structural weight. Figure 4 shows the wing structure designed for a low weight. In the whole of the structural design, the weight was the driving factor.

Propulsion Considerations

Propulsion is an important aspect of the aircraft. Indeed, with failing propulsion, there can be no successful mission. Most suitable is a brushless motor

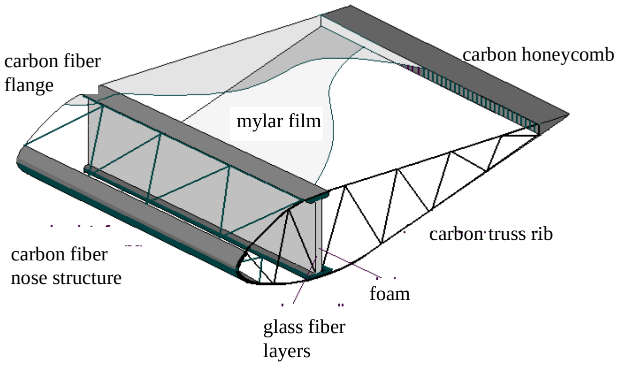

Figure 4: Wing structure.

because of its long lifespan and a high efficiency of 95%. This efficiency is assumed to be constant during its lifetime.

In order to reduce the loss of energy created by high temperatures in the motor, cooling is necessary. Because of the air stream created by the propeller, and because of the need of high reliability, passive air-cooling is very suitable. This can be placed around the motor just behind the propeller to use the propeller outflow as an inflow to cool the motor.

The new propeller was designed for high propulsive efficiency in cruise conditions (see Figure 5), with a speed of 25 m/s at a height of 18 km and generating just enough thrust to equal the drag of the complete aircraft. A propeller efficiency of 86% in cruise condition was obtained.

Figure 5: Sketch of the propulsion unit.

Design of the Computer Program

So as to preserve a clear overview in the enormous amount of used variables, an extensive *MatLab* computer program was developed and used in producing the final configuration results, which are listed in Table 1.

Figure 6 shows the use of the aircraft in a system where it replaces satellites for communication.

Table 1: Final configuration results.

Wing span Wing area	91.56 m 210 m^2
Total length Total height	29 m 7.1 m
Aspect ratio wing	40
Area tracking solar panels	2 times 120 m^2
Total mass	1,048 kg
Max. latitude (*year round service*)	59”
Achievable airspeeds 55” NB	22 27.8 m/s
Climbing time to cruise altitude	8 11 hours
Mass payload Continuous power consumption payload	100 kg 1000 W

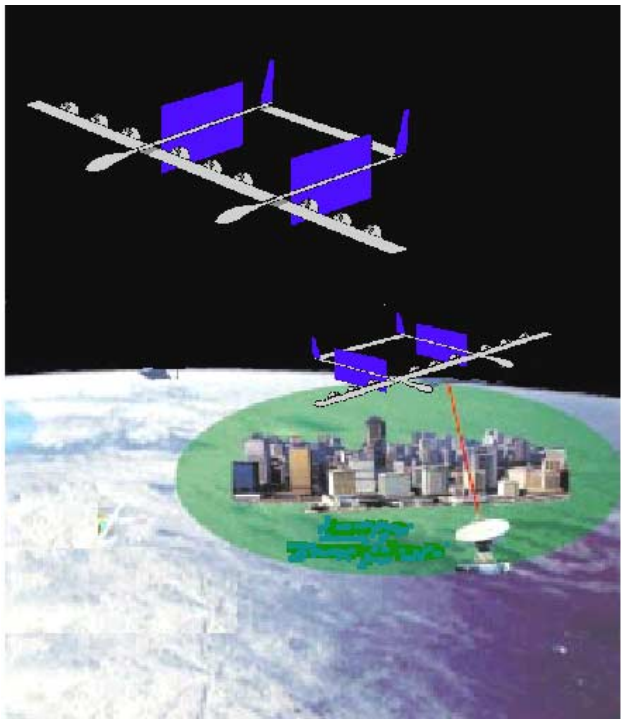

Figure 6: Possible application of the aircraft.

SUSTAINABLE DEVELOPMENT AS EXPERIENCED BY STUDENTS

Students, in general, look forward to the design and synthesis exercise at a point in time when they *feel* they are ready for such a complicated exercise. Up until that moment, they have taken mono-disciplinary courses and exercises. The design and synthesis exercise is the first time they will be confronted with such a challenging exercise. They all want to start designing aircraft and spacecraft and do not want to be *bothered* by other courses. Therefore, they feel the additional courses as being a real burden that take their attention away from what they feel as the main issue of the exercise.

Sustainable Development is one of these additional courses. This means that the teacher is being confronted with a difficult task in getting students to focus on the sustainability aspects in their designs. In the preparational phase of the exercise, the SD-teacher discusses those issues that are relevant with respect to Sustainable Development with the project coach. Together, they attempt to identify those aspects of the exercise that can be used best in the SD course.

Although this approach ensures that Sustainable Development is embedded in the exercise as much as possible, students' reactions are mixed. It can be seen that when a design assignment has many sustainable aspects built in naturally, students appreciate the course on Sustainable Development much more than otherwise. For instance, the assignment for the design of a Reno-racer, an aircraft designed to race between two poles at low altitude, maximum speed and requiring the use a maximum amount of power, and thus fuel consumption, resulted in a low appreciation of the SD course. The aspect of sustainability was brought into this specific exercise only in a way that students had to use recyclable materials as much as possible in their design.

On the other hand, the case described in this article resulted in a high appreciation of the SD course. The use of solar cells and only the sun as a means of propulsion instantly gave students a feeling of being involved in a sustainable design.

EVALUATION OF THE DESIGN AND SYNTHESIS EXERCISE

At the end of each year's exercise, students are requested to fill out a questionnaire that investigates all aspects of the exercise. It starts with the preparation and continues until the final marking. All additional courses are also tackled in the questionnaire. The focus in this article will be on the evaluation results of Sustainable Development.

The exercise was given to 13 groups, with all groups receiving a different assignment. The overall mark students gave the exercise was 77 out of 100. The mark for the additional course on Sustainable Development was 70 out of 100. In the questionnaire, students were also asked to grade the importance of Sustainable Development in their education as an engineer. They marked it with 65 out of 100. Finally, they were asked to mark the importance of Sustainable Development for this specific exercise; the average mark was 50 out of 100. It is worth noting that there was a wide spread between the groups, ranging from 25 to 73. The group used for the case study marked this aspect with an average mark of 47.

Students were given the possibility to comment on the exercise and all its aspects. Those comments referring to Sustainable Development almost all related to its integration in the exercise. They concluded that when Sustainable Development does not fit in naturally, it should not be given such a large amount of attention. Furthermore, the course was described as *being a bit vague*. These comments were the reason for the organising committee to reconsider the position of Sustainable Development within the design and synthesis exercise.

NEW DEVELOPMENTS

Since it was recognised that the integration of Sustainable Development into the design exercise caused problems, a new approach has been tested this academic year. This new training can be characterised as a series of workshops in which the design made in the entire design exercise will be the focal point. The basic idea is to design a future sustainable system that students will incorporate into their design. A four step approach will be taken for this.

Step 1 is a strategic problem orientation, where the problem is explored and the way to solve it is recognised. At the same time, a stakeholder analysis (identification of all people/groups that have something to do with the problem) is executed where each stakeholder's vision, needs and wishes are identified. It is important in this phase not to focus just on the technical aspects of the problem. It also has to be identified what needs could be fulfilled by using the technology or product being developed in the exercise.

Step 2 covers the development of an idea of how the defined needs can be fulfilled in the future. This involves moving to a moment in time 50 years from now and imagining what the world will look like. This broadens students' views and gives opportunities for creativity and inspiration. The extrapolation of current developments does not make sense anymore; a mental reset is needed. Imagining what the future would ideally look like is a must.

Students need to determine that the *system*, which makes sure that the needs that have been identified, is fulfilled and what it will look like. Their product or technology is part of this system. So it is not the aircraft itself, but rather the transport system, that is the subject. The future system that students define needs to be sustainable and complete. This means that no waste is coming out of the system on a structural basis, and the used energy and materials need to be refilled and/or recycled on an equal basis as they are used. Effects could also be social (eg living standards in now poor countries), cultural and political; they may also be related to other technical areas like chemistry, geology, medicine, religion, etc. The needs of future generations should not be endangered.

Step 3 incorporates the definition of the steps that are required in order to realise this future situation. In the end, this should lead to a series of realistic activities with a relative short time horizon. Together, these steps bring the sustainable future closer.

Step 4 involves the execution of short-term activities as already defined. These steps should be planned and executed as in integrated part of the remainder of the project. Of course, only those activities that are within their span of control should be executed, such as design changes. Other activities should be clearly defined and appear as recommendations in students' reports.

For those design assignments that are clearly not meant to be sustainable, a separate assignment on Sustainable Development is issued. In this alternative assignment, a so-called technology assessment needs to be performed. The possible effects of the technology developed should be assessed. There can be direct effects and indirect effects (spin-offs). These effects can be technical, social, cultural, etc. Both negative and positive effects have to be taken into account. In the case of negative aspects, students should formulate possible approaches in order to eliminate or mitigate these effects.

The benefit of this new approach is that Sustainable Development is tackled as part of a design generated by students. The sustainability aspects of the design itself are no longer isolated from the rest of the world. This should give students a wider perspective. The down side of this approach is that students still need to be motivated for this course, as it takes time away from the actual design itself.

Future evaluations at the end of the exercise will show whether or not this approach has been beneficial. However, the author believes that only when an assignment has a sustainable character, as in the case study presented here, students will then become motivated for Sustainable Development. When sustainability is not really integrated in the design assignment, it would be better to teach Sustainable Development as a separate course outside the framework of the design and synthesis exercise.

CONCLUSION

Many sustainable aspects were incorporated in the case study. The design specification required the aircraft to be totally dependent on solar energy alone and nothing else. This has put strong requirements on the efficiency of the propulsion and the structure. Sustainability is implicitly taken into consideration in this design.

Based on this design example, it can be concluded that incorporating sustainability in the design is possible. However, it largely depends on the design specification. Other design specifications do not allow sustainability to be incorporated that easily. This may be because the subject to be designed in itself is not sustainable, for instance a Reno racer aircraft, or where sustainability is not an issue in the design.

In the design and synthesis exercise, this often leads to *artificial* approaches where sustainability is brought into the design. In such a case, students immediately develop an aversion with respect to the subject; they do not see the benefit of sustainability and are no longer interested. They will only take the courses and do the assignments using minimum effort because they need to earn the credits. In the remainder of their study, they will avoid anything related to sustainability. Hence, a new approach where the design is incorporated into a system is now being tested.

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BIOGRAPHY

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