ME6105 - Modeling & Simulation in Design
Homework 2: Planning Your Simulation-Based Design Study

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Task 1: Identify the Decision Situation

Application Domain (Rapid Prototyping)

During the process of designing and developing systems with a physical character, especially such where the requirements cannot be clearly defined or open questions come up during the design process, it is often desirable to produce so-called prototypes. A prototype is an early sample or model, whose sole purpose is to learn from or to test a concept or process with. Up until the late 1980s, physical prototypes had to be produced in workshops, usually using so-called subtractive manufacturing techniques. These subtractive manufacturing techniques include processes such as milling, which remove material from a block of material to shape a desired part.

To reduce the cost and time of developing prototypes, an automatic construction technique called Rapid Prototyping was developed in the late 1980s. This technique makes use of additive manufacturing technology. Additive manufacturing is the process of constructing a physical artifact from 3D model data, layer by layer, using only raw material and energy. The 3D model data can directly originate from an engineer’s Computer-Aided Design (CAD) tool. During the process of constructing the prototype, successive layers of liquid, powder or sheet material are laid down and then fused together automatically to produce the final shape. This allows for the model to be built up from a series of cross-sections.

![Rapid Prototyping Machine and Part](image)

Figure 1.1: A rapid prototyping machine producing a part (left) [1] and a part produced using rapid prototyping techniques (right) [2]
The System of Interest

The system being considered for this simulation-based design study is a rapid prototyping machine. There are several competing technologies in the marketplace. All of these use additive techniques – their differences are mainly found in the way the individual layers are built: some rely on melting or softening material to produce the layers, others use liquid material that is then cured. Table 1.1 summarizes the different prototyping techniques available.

Table 1.1: Different rapid prototyping technologies

<table>
<thead>
<tr>
<th>Prototyping Technology</th>
<th>Base material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selective Laser Sintering (SLS)</td>
<td>Thermoplastics / Metals / Powders</td>
</tr>
<tr>
<td>Direct Metal Laser Sintering</td>
<td>Almost Any Alloy Metal</td>
</tr>
<tr>
<td>Fused Deposition Modeling (FDM)</td>
<td>Thermoplastics / Eutectic Metals</td>
</tr>
<tr>
<td>Stereolithography</td>
<td>Photopolymer</td>
</tr>
<tr>
<td>Laminated Object Manufacturing</td>
<td>Paper / Plastic Foils</td>
</tr>
<tr>
<td>Electron Beam Melting</td>
<td>Titanium Alloys</td>
</tr>
<tr>
<td>3D Printing (i.e. Inkjet)</td>
<td>Various Materials</td>
</tr>
</tbody>
</table>

For our simulation-based design study, we will only consider the Fused Deposition Modeling (FDM) technique. A rapid prototyping machine (or “printer” in that sense) implementing this technique consists of a nozzle (that dispenses the material used to build up the physical model) as well as some mechanism that allows for the relative movement between the nozzle and the table. In our example, we will be using a table that can be moved into the z-direction (down) and an arm that allows for the nozzle to move to any point on the x-y plane. See figure 1.2 for a schematic drawing of the system.

Figure 1.2: Schematic drawing of the FDM rapid prototyping machine considered in this simulation-based design study
Most FDM rapid prototyping machines dispense two different materials through the nozzle: the material used to build the actual physical model and an easy to remove (e.g. soluble) material to build a temporary support structure (this becomes necessary if the model has no flat surface to stand upright on during production). The physical artifact is built up from either a plastic filament or metal wire that is unwound from a coil and is supplied to the extrusion nozzle which can turn the flow on or off. Each layer of the model is as little as 0.125 mm (0.005”) thick. The material is heated in the nozzle and melts before being laid down as part of one layer. See figure 1.3 for an illustration on how individual layers are formed.

![Creating layers of a three dimensional physical model using the FDM technique](image)

**Figure 1.3: Creating layers of a three dimensional physical model using the FDM technique**

One of the great advantages of rapid prototyping (or, in that effect, additive manufacturing) is that almost any desired geometrical shape can be produced, with the desired precision depending on the thickness of the layers. Since the technology is still relatively new, it can take several hours – sometimes even days - for a physical model to be produced.

**Specific Design Decision**

Nowadays, rapid prototyping machines are available in all sizes: from large industrial rapid prototyping machines that can even produce car parts (e.g. the Audi RSQ from the movie “I, Robot” was made using rapid prototyping techniques) to desktop sized machines that can quickly and easily “print” a physical three-dimensional model. Priced at around US$ 10’000.00, desktop manufacturing is becoming affordable enough even for at home inventors. Some
institutions and companies have released plans and kits to build rapid prototyping machines, with some costing even less than US$ 500.00 to build (see e.g. the RepRap project).

Unfortunately the low cost of such home-made rapid prototyping machines comes with a price: relatively low precision. Other commercial desktop sized rapid prototypers, on the other hand, allow for models to be built up with a relatively high precision. Since the runtimes of a build can be relatively long, a rapid prototyping machine should be reliable and robust.

Within this simulation-based design study, we will focus on a desktop sized prototyping machine. Our goal is to determine the characteristics of the motors for the positioning mechanism (torque, speed) to minimize the time to move to a specific point as well as maximize the stiffness of the mechanical structure used to position the nozzle (by selecting a beam type and the thickness of the beam), thereby maximizing the achievable precision. Furthermore, we will be looking at minimizing cost (both of the components and the power consumption) and minimizing mass, both of which will have an effect on the maximum stiffness.

**Verify Scope of Decision Scenario**

The decisions that will be made with this simulation-based design study are confined to the mechanical structure and how it affects precision and cost. Therefore, the decision scenario can be scoped within the authority of the decision maker who, in this case, can be considered a mechanical engineer. Note that other factors such as retail price, aesthetics and other aspects of the system are not considered.
Task 2: Determine an Objectives Hierarchy

The greatest value for a company building this type of portable 3D-Printer is to maximize profit; therefore, maximizing profit was chosen as the fundamental objective for this project. In discussing the decomposition of this objective, the team found that maximizing profit is a straightforward objective and cannot be easily broken down into more specific fundamental objectives. Hence, the team decided to focus on this one main value.

![Figure 2.1: Fundamental Objective](image)

Although there is only one fundamental objective for this project, a large number of means objectives were found. These included minimizing cost, maximizing speed, maximizing accuracy, maximizing precision, maximizing build space, maximizing durability, etc. and are organized in the means objective network on the next page. These objectives certainly do not encompass all of the means objectives which could be explored, but rather exemplify some of the ideas discussed.

From these objectives, the team chose four key objectives that stood out as important, having measurable attributes, and fitting within the scope of this project. First, maximizing speed was chosen with an attribute of time to a selected position in seconds. Speed of a 3D printer is important because customers desire to build parts as quickly as possible; therefore, increasing speed will create a more desirable product. Also, the speed of the nozzle is a large factor in sizing the motors. Second, minimizing production cost was chosen because of its direct effect on profit as well as its effect on pricing and hence demand. Total component cost in dollars was chosen as the attribute for this objective. Third, maximizing precision with its attribute position overshoot in millimeters was chosen because of the customer desire of precise parts. Precision is also very important in a printer of this size because of its effect on the ability to make small parts. Finally, minimizing weight was chosen because of its opposition to precision in the case of frame stiffness. A stiffer frame will create less overshoot, but this printer is intended to be portable and therefore lightweight. The attribute chosen for this objective was total mass of the printer in kilograms.
### Table 2.11: Key Objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximize Speed</td>
<td>Time to Position (sec)</td>
</tr>
<tr>
<td>Minimize Production Cost</td>
<td>Total Component Cost ($)</td>
</tr>
<tr>
<td>Maximize Precision</td>
<td>Position Overshoot (mm)</td>
</tr>
<tr>
<td>Minimize Weight</td>
<td>Total Mass (kg)</td>
</tr>
</tbody>
</table>
Maximize

Profit

Minimize

Cost

Maximize

Durability

Minimize

Operation Cost

Maximize

Robustness

Minimize

Production Cost

Maximize

Life Cycle

Maximize

Speed

Maximize

Build Space

Minimize

Vibration

Maximize

Table Size

Maximize

Precision

Maximize

Frame Height

Maximize

Control

Maximize

Positioning

Minimize

Weight

Minimize

Production Cost

Maximize

Motor Power

Maximize

Frame Height

Maximize

Motor Power

Maximize

Responsiveness

Maximize

Viscosity

Maximize

Stiffness

Maximize

Accuracy

Figure 2.2: Means Objective Network
Task 3: Identify the Design Alternatives

Scope of Problem

As described in the introduction, fused deposition modeling consist of multiple subsystems that for the purposes of this project would take too long to develop a comprehensive model, and will therefore be limited to the nozzle positioning system (namely the motors) and the stability of the structure (beam classification). Even with respect to these systems, there could be a ballooning of potential design variables such as motor resistance, current consumption, and various potential structural layouts. We have therefore chosen to limit the chosen design parameters to only those which relate directly to purchasing components, and can still be related to an energy based system model.

For our current setup we will be selecting an individual motor for each Cartesian direction (x, y, z). The design alternatives for each of these motors will be motor speed and motor torque. These variables will related directly to all of the objectives, as both torque and speed with have an impact on build time, larger/higher performance motors add to cost and mass, and more greater acceleration will affect put greater force on the structure. The specific variables that will be determined for the structure are the size of beam and the type of beam. These variables will relate to the cost, precision and mass objectives. In determining each of these variables, it will be necessary to make sure the parameter options reflect real world components that can be purchase.

To reiterate the design variables to be investigated are listed below:

- Motor Speed
- Motor Torque
- Beam Type
- Beam Size
Task 4: Identify the Structure of the Design Problem

Chance events are something that the engineers/decisions makers have no control over. Some of the chance events for the design of rapid prototype machines are as followed:

- **Economic Climate**: Economic climate affects the supply and demand of the machine and therefore influences the sale and profit. In addition, it also affects the cost of raw materials, parts and subassemblies which influence the production cost of the machine.

- **Competitors’ alternative**: We have no control over the competitors’ doings. They potentially can increase the supply in the market which will adversely affect our sale and profit.

- **Durability**: Durability is not completely a chance event. There are things we can do to improve durability. However, the followings are chance event that will affect durability
  - **Manufacturing Defects**: Manufacturing defects are defined as frailty or shortcoming in a product resulting from a departure from its design specifications during production. They can only be controlled to a certain extent.
  - **Users’ behaviors**: Misuse/abuse can adversely affect the durability of the machine.

- **Backlash in lead screw**: Backlash is described as the amount of lost motion due to clearance or slackness between mating components when movement is reversed and contact is re-established.

Several intermediate computation outcomes exist for the design of rapid prototype machine. The main calculation that affects the overall profit utility is the supply, production cost and machine performance. Some calculations that influence the machine performance include build time, overshoot in inches, mass of the machine and power consumption.

Figure 4.1 shows the influence diagram to model the relations between all the decision elements in the design of rapid prototype machine.
Figure 4.1: Influence Diagram for the rapid prototype
Task 5: Identify the Simulation Scenario for an Energy-Based System Model

Two of the key design objectives chosen require an energy-based model to relate to the design alternatives: maximize speed and maximize precision. Maximizing speed requires an energy-based model to analyze the movement of the nozzle and predict the required motor torque and motor speed. In addition, maximizing precision requires a model of the frame stiffness, bending, and vibration to predict the overshoot of the nozzle. This allows precision to be related to beam thickness and beam type. Minimizing weight may be examined with an energy-based system or a simpler sum may be used. This objective will also relate to the beam thickness and beam type attributes. Finally, production cost does not require an energy-based model, but will be calculated by a simple summation of the costs of the components.

Maximizing speed and maximizing precision will be modeled in Dymola in homework three. The team will assess whether to model the weight in Dymola or sum the various masses as more is learned about the modeling process. The model will include the physical phenomenon of beam bending in the frame to predict the precision. In addition, the backlash in the lead screw will be modeled. Rotational and translational energy domains will be considered in the movement of the motors and nozzle, as well as the transition between the two. Some electrical components may also be used in the motors.

To limit the scope of the project, many assumptions must be made. The most significant is in the controller for the motors. The team plans to model the controller with infinite gain so that overshoot of the nozzle will only be due to bending in the frame. In an actual system, a controller would have to be designed and would most likely have some effect on overshoot. Also, the team plans to ignore the effects of the printing material flow through the system. The nozzle will be designed with a constant mass. These effects would likely be very complicated and much beyond the scope of this class; however, the team feels that the effects are likely to be small and therefore feels comfortable with this assumption.
Task 6: Assess your Plan

Uncertainty and Contingency Plan

There are multiple aspects of this project which present uncertainty, and could lead to problems with modeling the design as well as linking back to our objectives. The major areas of uncertainty we predict within our model are related to the lead screw positioning, and the controller for the motors. As stated previously, lead screws will be used to transform rotational motion of the motor shaft to translational motion of the nozzle. Because all lead screws have some backlash, it could be very difficult to know the true position of the nozzle within this tolerance, which will affect the precision of our printer. In developing this model we must include a controller for the motor positioning. We did not wish to include the controller parameters as part of our design variables, and therefore propose selecting an infinite gain for our controller, which would make any overshoot in the system a result of the motor selected and the frame stiffness. There is potential that this approach will not work, and we would therefore have to investigate how to optimize the controller. Our first solution would be to switch from a feedback system to a feed forward system. If this is also unsuccessful, we will expand our scope and try to tune the controller.

Another area of uncertainty is with our cost and demand modeling. To successfully achieve the objective function for cost minimization relative to a real world system, it is necessary to know the component costs, labor cost, energy costs as well as demand. Additionally, we have yet to determine how to integrate cost considerations into our model of the physical parameters and relate it to our other objectives. Our contingency plan for dealing with these issues includes using generic assumptions from literature to develop reasonable cost and labor estimates, and if necessary, simplifying our cost objective function to only component cost which could tentatively be found from online vendors. Finally, if we are unable to link these cost parameters to our other objectives, we may have to exclude this objective in our final decision and look solely at performance utility.
Task 7: Articulate your Learning Objectives

Jason Nam Nguyen

Life is about choices and making decisions. Decision making is even more important in design engineering. My long-term career goal is to become a project manager where I would have to make decisions regarding the project on the daily basis. Modeling and simulation has become absolutely necessary for the decision making process. At the end of the course, I hope to learn how to make decision that would lead to the most desired result through modeling and simulation by defining objectives and design decision and considering possible design alternatives. I also hope to gain hand-on experience with Dymola and Modelica to model and simulate design problems of interest.

Sarah Shields

As a future design engineer, I hope to learn through this project how to best make design decisions to create superior parts. Also, to learn where the techniques learned in this class can be applied. In addition, I hope to learn how to break problems down into logical parts that can be easily modeled and designed. Learning to make appropriate assumptions and simplifications is also part of this process. Finally, I hope to learn the basics of Dymola and Modelica in implementing energy-based systems modeling.

Chad Hume

After reading the first chapter of the course text I strongly agreed with changing my viewpoint away from wanting to be a problem solver and shifting to be a decision maker. Upon completion of my PhD I am unsure which direction I want to go, whether it be academia, R&D or maybe even management consulting. Though one thing that all of these areas have in common is that in order to be successful and take on more responsibility one needs to be able to effectively and efficiently make decisions, and make the right ones. My first major objective for this course is therefore, to learn and internalize a systematic and mathematically sound method for making decisions which lead to the best possible outcome. I also believe that due to the complexity and cost of prototyping many current systems, modeling and simulation has taken on a huge role in the product development arena. By using an object oriented modeling language, like Modelica, a technically sound model can be generated and tested in a more cost effective manner, most of the time, to give a general idea for parameter values and initial concept validation. My second objective is therefore to learn the Modelica language through application in this project.
Sebastian J. I. Herzig

When confronted with the task of having to design and develop a system (or even just a part of it), a designer is often confronted with the task of having to select among several alternatives. A decision must then be made which alternative concept to further refine. But which alternative would lead to the most desired outcome, i.e. how do we make a good decision? As a PhD student researching on Model-Based Systems Engineering, this is a challenging, yet very common problem. Properly defining objectives, and modeling and simulating a system of interest is an essential part of the decision making process. By taking this course, I hope to be able to understand more deeply what process leads to the most desirable outcome and how such a decision-making problem can be structured and defined formally. Furthermore, I hope to be able to gain some experience with object-oriented modeling using Modelica. Last but not least, I also hope to gain experience in practically applying optimization algorithms and, in the process, learn more about ModelCenter and its integration capabilities with other tools.
References
