The Design of a Competitive, Hydraulically-Powered Excavator

ME6105-Modeling and Simulation in Design

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1. Decision Situation

The objective for this assignment is to develop a plan for a simulation-based design study of a hydraulically-powered excavator. Hence, for this study, the main application domain of industrial hydraulics is being considered. Commonly, excavators are driven by a single diesel engine that supplies power to a variable-displacement pump. This pump, in turn, feeds pressurized hydraulic oil to a series of actuators that drive the physical motions of the system. Typically, two identical hydraulic cylinders drive the main boom, a single cylinder drives the arm, another single cylinder drives the bucket, a hydraulic motor rotates the base, and hydraulic motors drive the tracks which allow the excavator to change its position in the work site. By ignoring the motors which drive the tracks, the system under consideration consists of four hydraulic cylinders; a constant-displacement, hydraulic motor; a variable-displacement hydraulic pump; and a diesel engine that powers the whole system.

This system of hydraulic components is arranged in a load sensing, pressure compensating circuit. A schematic of such a system can be viewed below in Figure 1.

Source: http://www.hydraulicsupermarket.com/load-sensing.html

Figure 1. Typical load sensing, pressure compensating hydraulic circuit.
Figure 1 depicts a circuit that drives only two actuators. In this design problem, the actuator circuits would be repeated two more times to allow for the control of the two other motions of the excavator. One repetition of the circuit would equally control two cylinders corresponding to those that drive the boom. Given that this is the prescribed circuit architecture, the design decision will be based at the hydraulic component level (i.e. determining the characteristics of the actuators, pumps, and diesel engine).

While the design decision may seem to be scoped too broadly, necessary assumptions have been made in order to scope it within the authority of the decision maker, who is assumed to be hydraulics engineer. Rather than factoring on variables such as retail cost, aesthetics, and other factors that contribute to the competitiveness of the product, the scope has been narrowed down to determining the competitiveness of the excavator’s behavior. Also, major chance events will be simplified into models, but only influencing decisions that are of major concern to the engineer.

2. Objectives Hierarchy

The fundamental objective for the excavator design project can be broken down into the hierarchy displayed in Figure 2 below.

![Objective Hierarchy Diagram](image)

Figure 2. The fundamental objectives hierarchy for the excavator design project.

The main fundamental objective that we are striving to fulfill in our design study is to create a competitive excavator. We define what this means to us by breaking this main objective into
two sub-categories, which are minimizing cost and maximizing performance. The cost minimization objective refers to minimizing operating cost as well as construction cost. The performance maximization objective refers to minimizing cycle time while maximizing efficiency.

In order to achieve these fundamental objectives, a means objectives network has been derived and is shown below in Figure 3.

![Means Objectives Network](image)

**Figure 3.** The means objectives network for the excavator design project.

This network illustrates our means objectives, which are the objectives that explain how we plan on achieving our main, fundamental objectives. The objectives in our network that are the most significant to us pertain to minimizing operational cost, minimizing construction cost, maximizing efficiency, and maximizing reliability. We chose these because they best define how we plan to develop a competitive excavator. We plan to measure operational cost by comparing it to power consumption. The total power consumption will be determined as a
product of required pressure and flow rate. Efficiency will be measured by comparing a required load to the corresponding power consumption. Construction cost will consist of the cost of the actuators, pump, and the diesel engine. For the hydraulic components, we will be relating the part costs to respective parameter selections. For the diesel engine, we will be comparing the part cost to the peak power output. Reliability will be the most difficult to measure. However, we plan on researching hydraulics literature and statistics books on how to measure the reliability of hydraulic systems. We currently believe that there is a correlation between the size of the hydraulic components and their maximum required loads. In summary, we believe that all of these attributes can be modeled easily with the exception of the reliability.

3. Design Alternatives
The hydraulic system that drives the excavator will be modeled as a load sensing, pressure compensating circuit. Consequently, since the architecture of the fluid power circuit is predefined, the decision alternatives will exist at the hydraulic component level. The components in question consist of the actuators that power the system, namely: the two identical, hydraulic cylinders that drive the rotation of the boom; the hydraulic cylinder that drives the rotation of the arm; the hydraulic cylinder that drives the rotation of the bucket; and the constant-displacement hydraulic motor that powers the rotation of the excavator base.

Initially, the design variables to be analyzed reflect interests in the five actuators mentioned above. The bore diameters of the hydraulic cylinders have been selected as the design variables that best characterize the cylinder performance. The volumetric displacement per revolution has been chosen as a design variable that best characterizes the performance of the hydraulic motor. These parameters constitute five design variables; however, by applying the assumption that the boom cylinders are identical, the design variables are decreased to four.

These design variables will first be tested with a variable-displacement, idealized hydraulic pump. Under predetermined load conditions, the actuator parameters will be designed while maintaining that the pump can output an infinite amount of pressure and fluid flow. Upon completion of this task, the ideal pump assumption will be dropped in order to allow for the design a realistic pump subject to power input from a diesel engine. The maximum displacement
per revolution has been selected as the design variable that best characterizes the variable-displacement pump.

As mentioned above, a diesel engine will be providing power to the pump. The fuel consumption will be modeled as a function of output speed and torque. This will enable the analysis of output hydraulic power versus fuel consumption. The design parameters that characterize the performance of the diesel engine will most likely be fixed values not to be considered in the design project; however, inclusion of the engine could allow further design variable selection if deemed necessary.

4. Structure of the Design Problem
While structuring the design problem, many chance events exist that cannot be accurately understood or taken into proper consideration. Some events play minor roles in the design process while others can have large affects that, when underestimated, can pose detrimental effects to the overall design. Examples of such major chance events are fuel price fluctuation, the current economic environment, the environmental conditions to which the excavator will be subject, and the work characteristics of a given excavator operator. While playing a major role in the profitability of an excavator design, the economic environment appears to be the hardest to consider. Additionally, it seems to be considered best by modeling the price of fuel as an uncertain parameter. The other two chance events can be considered by characterizing them as variables with attached uncertainty. The effects of these events on decision outcomes are visualized in the influence diagram in Figure 4.
In the above influence diagram, the blocks to the left identify the design decisions that are considered in this project. All of these decisions directly affect the efficiency, production cost, and reliability of the system. Even though it could be argued that direct correlation exists, an assumption has been made that describes the operating cost as an indirect outcome of the design decisions by way of the system efficiency while also being influenced by three chance events, namely: fluctuating fuel prices, environmental conditions, and operator characteristics. Reliability is also believed to be affected by the environmental conditions and operator characteristics. The competitiveness of the excavator is directly affected by the four outcomes of the three design decisions. Customer demand, which is assumed to be outside of the scope of this project, is determined by the competitiveness of the excavator and the current economic conditions. Overall profit, while affected by many elements, can be represented by a simplified product of customer demand and excavator competitiveness.

5. Simulation Scenario for an Energy-Based System Model
The maximization of efficiency requires an energy-based model to relate it to decision alternatives. Efficiency is often described by the relation
where $E_{\text{out}}$ is the “useful” energy a system outputs (in this case the total work the excavator performs) and $E_{\text{in}}$ is the total energy the system requires to operate (in this case the fuel for the diesel engine). For this study, $E_{\text{out}}$ is constant; that is, each excavator design alternative is subjected to the same loading conditions to simplify the calculation of the efficiency. Thus, the efficiency maximization problem is simplified into finding the design with the minimum $E_{\text{in}}$ required to complete a task. The efficiency of the excavator will be addressed in the second part of the simulation-based design project, which is the modeling of energy-based systems.

Since the characteristics of each component in the hydraulic system of the excavator are determined by the decision alternatives, and each of these components can be modeled individually in terms of energy, efficiency of a particular design of the excavator can and should be modeled by an energy-based model.

Apart from the efficiency, the operating cost of the excavator can also be modeled by an energy-based model. The operating cost of the excavator depends largely on the efficiency of the system, as a more efficient excavator will require less energy to operate, therefore improving the operating cost. The operating cost will also be modeled in the second part of the simulation-based design project.

The energy domains that will be considered in the model are the hydraulics, rotational mechanical, and translational mechanical energy domains. Combustion and the effects of fluid flow are physical phenomena that would also be considered in the model.

The movement of the excavator base, the boom, the arm, and the bucket depends on hydraulic motors and hydraulic cylinders. The dimensions of each cylinder and the motor displacement will cause a trade-off between pressure and volume flow, and will be considered in the model. Apart from the hydraulic components, another energy domain that will be considered in the model is mechanical energy. Hydraulic actuators provide translational mechanical energy in
order to cause rotations of the boom, the arm, and the bucket. Additionally, a hydraulic motor provides rotational mechanical energy to rotate the base.

The energy of the excavator is provided by a diesel engine through the combustion of fuel, and this is a physical phenomenon that will be considered for the simulation.

Fluid pressure plays a major role in the model, as leakage is a problem that plagues hydraulic systems. Leakage, or an unintended drop of fluid pressure, occurs in every component of the hydraulic system of the excavator. Pipes, actuators, pumps, and valves cannot be idealized to neglect leakage as they play a major role in the design decision.

No models are ever exactly true in the sense that they make no assumptions, and this model is no exception. Some significant assumptions that affect this model are the fixed physical dimensions of the excavator, the required load cycles, chance events like fuel price and economic climate, and excavator operator characteristics.

Since this design project is a continuation of work done in a previous semester, it does not make sense to re-invent the wheel by designing new geometry for the excavator. Also, it is logical to assume that an existing excavator model exists and this project only serves to improve the efficiency of the hydraulic system. Thus, properties such as geometry, mass, and material of the excavator are fixed. Another consideration is that the hydraulic engineers working on the project most likely will not have the authority to change such parameters. All of this justifies the consideration of only the dimensions for the actuators and the pump characteristics.

Excavators can be used for various tasks, and each task will have its own loading conditions. For this study, we will assume this as it is impossible to consider all possible uses of the excavator.

An idealized pump will be used initially to determine a set of actuator design parameters. This assumption is imposed in order to simplify the problem without being constrained by the pump’s
design parameter. After the actuator parameters have been assigned, a realistic pump which can handle the required loading conditions will be selected.

Chance events can sometimes change the competitiveness and operation of the excavator; however, such events are difficult to predict, and is impractical to model in this design study. Fuel prices fluctuate unpredictably; thus, if fuel prices go up, a powerful excavator may seem undesirable when compared to an energy efficient excavator. For this study, the current diesel price would be taken as a constant with assigned uncertainty.

Different operators have different characteristics in the way they operate an excavator: one may be gentler on the controls while another may be more aggressive. For this study, since a more aggressive operator puts more strain on the system, such an operator will be modeled.

6. Plan Assessment
While assumptions have been made in order to limit the overall number of variables, there are still a few uncertainties in the current plan. The decision to initially utilize an idealized pump (rather than addressing pump characteristics) provides a solid base for expanding the content of the project. If the project turns out to be too complex, the idealized pump will be used to reduce complexity while maintaining an approach for establishing optimal values for the four design variables characterizing actuator performance. At this point, however, the design of the pump parameter should be a feasible task.

At this point, modeling the diesel engine is another primary goal that seems feasible. Assigning a design variable to the diesel engine would introduce more realism into the project; but, the current plan is to model the performance of the engine using fixed characteristics.

If time permits, a valveless hydraulic circuit (consisting of four, independent variable-displacement pumps corresponding to the four actuator-induced movements) could be addressed as an additional design alternative. Currently, however, the focus of the project will remain on the design of the load sensing, pressure compensating circuit and its components.
7. Learning Objectives

7.1. Rashid Enahora

My major for my graduate study is design. I took ME6101 last semester and learned the Pahl and Beitz systematic design process. One of the main objectives in that class was to augment and personalize this process so that you it would be applicable to a globally distributed design environment. The assumption made in this class is that globally distributed design will become dominant and extremely important in the future. One thing that ME6101 emphasized was that decision making must be implemented into the design process that we augmented. My main objective in Modeling and Simulation is to use the skills that I gain from this class to improve my decision making skills. In industry there are many open ended problems where the problem is not well defined, but yet complicated decisions must be maid. I will like to learn how these complicated problems can be converted into smaller problems so that I can make easier decisions.

7.2. Thomas Johnson

In order to increase my ability to perform commendable research in graduate school, my learning objectives reflect areas of my undergraduate education that require refinement and additional knowledge. As an undergraduate, I learned a substantial amount about fluid dynamics, but little about the implementation of fluid power systems. Knowing the fundamentals of fluid dynamics is useful, but my ability to study the design of fluid power systems would be greatly aided if I knew more about the configuration of common hydraulic circuits. In response to this, I plan on refining my knowledge of fluid power by studying, modeling, and making design decisions about the circuits, actuators, and control elements of the excavator.

At the undergraduate level, I was also introduced to systems modeling and design, but I feel that these classes lacked contemporary content. For example, my modeling class utilized bond graphs in the creation of differential equations that model system behavior. Even though this approach produces appropriate behavioral models, using the Modelica language employs a more modern, powerful, and intuitive approach to modeling system behavior. Additionally, my undergraduate education did not cover common design and optimization practices. From this project, I want to
learn about the formulation of design problems and the inclusion of parameter uncertainty in the optimization process.

7.3. Ivan Lee
The project I am working on is to improve the existing hydraulic system in an excavator. Coming into this course as an undergraduate in Mechanical Engineering, I do not have a strong background in hydraulic systems. Thus, in working on the project in this class, one of the main learning objectives for me is to gain further understanding on hydraulic systems. Through reading textbooks and online references, I have already gained some knowledge in how various hydraulic components and their systems operate and modeled. During the course of the class, I hope I will gain more in-depth knowledge of such systems.

Another area I am looking to be a major learning objective for me is how to model a decision. In the industries, most decisions are made to make more profit, but from my knowledge I have gained in my undergraduate studies, there is a disconnection between how physical phenomena and business relates. This is because in most of the undergraduate courses I took, the emphasis has been on modeling accurately various physical phenomena. The extent of the model is often limited to the realm of the particular physical system. How other physical systems, risk, uncertainty, and cost are incorporated the model is a question that I want to be able to answer by the end of the course.

7.4. Dan Sankar
For this course, I would like to emphasize the overall design decision process as a learning experience. Since I wish to pursue a career in design, I feel like this course will be a tremendous benefit for my future and will give me a glimpse into what I may deal with once I step out into the real world. Learning how to model and simulate systems, especially in which physical testing is infeasible, would be an invaluable learning experience that I will reference and hopefully improve upon throughout my career.