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COMPARING PROBLEM-BASED LEARNING AND LECTURE AS METHODS TO TEACH WHOLE-SYSTEMS DESIGN TO ENGINEERING STUDENTS

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COMPARING PROBLEM-BASED LEARNING AND LECTURE AS METHODS TO TEACH WHOLE-SYSTEMS DESIGN TO ENGINEERING STUDENTS.

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master's of Science
Civil Engineering

by
Michael Dickey Dukes
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Accepted by:
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ABSTRACT

The objective of this research is to compare problem-based learning and lecture as methods to teach whole-systems design to engineering students. A case study, Appendix A, exemplifying successful whole-systems design was developed and written by the author in partnership with the Rocky Mountain Institute. Concepts to be tested were then determined, and a questionnaire was developed to test students' preconceptions. A control group of students was taught using traditional lecture methods, and a sample group of students was taught using problem-based learning methods. After several weeks, the students were given the same questionnaire as prior to the instruction, and the data was analyzed to determine if the teaching methods were effective in correcting misconceptions. A statistically significant change in the students' preconceptions was observed in both groups on the topic of cost related to the design process. There was no statistically significant change in the students' preconceptions concerning the design process, technical ability within five years, and the possibility of drastic efficiency gains with current technologies. However, the results were inconclusive in determining that problem-based learning is more effective than lecture as a method for teaching the concept of whole-systems design, or vice versa.

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Project Description

Comparing problem-based learning and lecture as methods to teach whole-systems design to engineering students.

1 INTRODUCTION

The objective of this research is to compare problem-based learning and lecture as methods to teach whole-systems design to engineering students. The research is introduced in the following subsections (1.1-1.4), and described in detail in Sections 2 through 4.

1.1 Background and Need

Whole-system design is recognized as being more conducive to sustainable designs than current design practices. Current design practices tend to focus on the optimization of siloed pieces of the entire system. (RMI) Whole-system design takes into account the efficiency of a system in its entirety, rather than in bits and pieces. The whole-system approach also considers capital and operating expenses of the system as a whole. Case studies of projects that were initially designed using conventional methods, and then redesigned using a whole-systems approach, resulted in more sustainable, cost effective solutions. In order to have widespread change from siloed design practices and implement whole-system design, future engineers must be taught the more sustainable and efficient method of design beginning at the start of their academic careers. Therefore, the goal of this research is to compare problem-based learning and lecture as methods to teach whole-systems design to engineering students.

1.2 Work Plan

The work plan is as follows:

- Identify and develop a case study of an effective whole-system design
    - Working with Rocky Mountain Institute (RMI[1]), a case study was developed of an existing industrial facility, which used whole-system design to attain an efficiency gain of 86% over the facility's original design.
- Determine students' preconceptions
    - A questionnaire was developed to quantitatively determine students' preconceptions about sustainable engineering and whole-systems design.
- Introduce the case study

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[1] RMI – Rocky Mountain Institute® (RMI) is an independent, entrepreneurial, nonprofit think-and-do tank™. We envisage a world thriving, verdant, and secure, for all, forever. To that end, our mission is to drive the efficient and restorative use of resources.

  - The case study was presented to two separate sections of engineering students in a class being taught by Dr. Leidy Klotz of the Clemson University Civil Engineering Department. One class was taught using the traditional lecture method and was the control group. The other class was taught and introduced to the case study using problem-based learning techniques. Each class was one 50 minute period and the contents are presented in Appendix C.

- Assess the change in preconceptions

  - A second questionnaire with the same questions as the first was completed by the students' after the material had been completed. Following the questionnaire, a group of students was interviewed about the reasoning behind their responses. The before and after results of students' perceptions was then be compared. The information obtained during the focus groups was used to recommend refinements to the teaching methods during future iterations of the research.

- Evaluate the effectiveness of this method and suggest improvements to replicate this study for other cases and other students' study of sustainable design.

In order to accomplish these tasks, the Civil Engineering Department and RMI were consulted. RMI provided information for case studies involving whole-system design. The Civil Engineering Department provided faculty to assist in teaching the case study to students. The students in two sections of a Civil Engineering class served as the test subjects for this research.

1.3 Outcomes and Evaluation

In order to evaluate the change in students' preconceptions regarding sustainable engineering and whole-system design, measures have been developed to assess the students' preconceptions of whole-system design, and how those preconceptions changed after being taught the case study. Upon completion of the research, a comparison of problem-based learning and lecture as methods to teach whole-systems design to engineering students will have been completed.

1.4 Expected Results and Dissemination

The following expected results will advance knowledge related to implementing problem-based learning to teach whole-system design in engineering education:

- Improved understanding of the benefits of whole-system design

- Suggested improvements to replicate this study for other cases and other students' study of sustainable design
- Case study demonstrating the benefits of whole-system design that is appropriate for publication within engineering education curriculum

To ensure a long term impact of the case study, it was developed in conjunction with RMI for the purpose of being implemented in a book of case studies demonstrating the benefits of whole-system design. The casebook being compiled by RMI will convey the benefits of whole-system design by presenting an engineering problem that was first solved using conventional design practices, and was then re-engineered using a more efficient whole-system design approach.

2 BACKGROUND AND NEED

This chapter explains the differences between traditional and whole-systems design and explains why there is a need for more widespread implementation of whole-systems design. This, in turn, supports the need to compare problem-based learning and lecture as methods to teach whole-systems design to engineering students.

2.1 Sustainable Engineering

In order to fully understand the importance of sustainable engineering, one must first have a grasp on exactly what is meant by the term “sustainable engineering.” The 1987 Brundtland Report defines sustainable development as “meeting the needs and aspirations of the present without compromising the ability to meet those of the future.” (World Commission on Environment and Development 1987) However, this definition was left rather vague and open for interpretation based on more localized constraints, which eventually led to the development of the Triple Bottom Line, represented in Figure 1. This theory builds on the Brundtland Report definition by breaking the goal into the three components of sustainable development; environment, economy, and society. The underlying principle of the Triple Bottom Line is that sustainability does not only address concerns for the environment, but also social and economic ramifications (Parkin 2003). Only when a new product’s or process’ impact on all three aspects is considered, can it be determined whether or not it is sustainable. Based on this approach to sustainable development, sustainable engineering is defined as “ensuring the sustainability of the entire commercial spectrum, from product to planet, across the Triple Bottom Line of socio-, enviro-, and econo-sustainability.” (Short 2008)

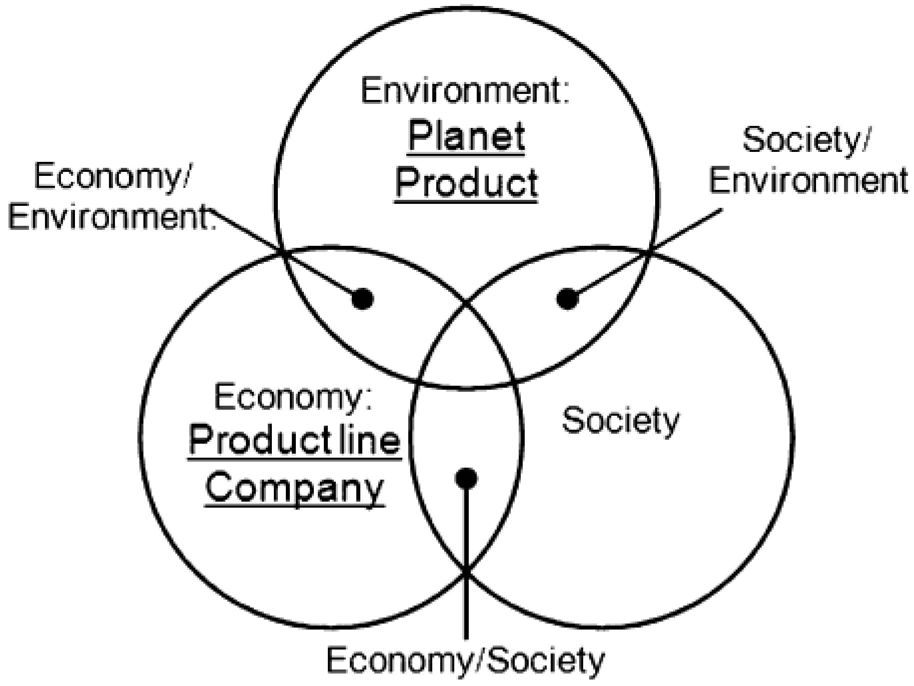


Figure 1. The commercial spectrum and its place within the Triple Bottom Line of sustainability.

Figure 1 – Triple Bottom Line. (Short 2008)

Implementing the concepts of sustainable engineering into students’ undergraduate curriculum will be a vital part of producing engineers that are capable of providing future generations with designs that will be more energy efficient and place less stress on the earth’s environment. In meeting these design goals, all three areas of the Triple Bottom Line are addressed, resulting in sustainable development. Rather than compartmentalizing sustainability by implementing a single course into the engineering curriculum focusing on sustainable engineering, it is important to implement sustainable engineering in a manner that reaches across all disciplines of engineering. Now, more than ever, it is important to train engineers to work with a broad range of disciplines, and therefore sustainability must also be taught in a manner that can reach all disciplines. (Lourdel 2005, Fokkema 2005)

2.2 Addressing Preconceptions

To effectively teach the material that will be presented to the students, an understanding must be gained of the students' preconceptions. The purpose of this is two-fold; it is vital to the research that the student's preconceptions be understood in order to determine if the case study is effective in correcting misconceptions that students may have about sustainable engineering and whole-systems design; it is also important to be knowledgeable of students' preconceptions in order to more effectively teach the material. (Mestre 2001)

Professors should seek to acknowledge and engage with the students' perceptions of learning and the subject when students exhibit some knowledge of the material (Lucas 2004). By building on what students already know, they will better comprehend the material than if it is taught in a manner inconsistent with their prior knowledge. However, students' may also have incorrect preconceptions, or misconceptions. These misconceptions may cause a resistance to learning since the material will be contradicting how the student currently thinks, but the misconceptions must be forcefully corrected so that the student will leave with a proper and accurate understanding of the material (Lucas 2004, Wankat 2002).

In an effort to set a base model for a method of teaching the case study, some common preconceptions have been identified by reviewing prior studies into college students' perceptions about sustainable engineering. The most common misconceptions that were discovered were the following: sustainable engineering is more expensive than current practices, sustainable engineering will be important in future generation but is not currently of importance, and technology will come along that will solve any problems created by current engineering practices. The final obstacle encountered in the previous studies was not a misconception, but a mere lack of knowledge on the subject matter of sustainable engineering (Azapagic 2005, Higgitt 2006).

While it is true that sustainable projects have the possibility of costing more than traditional design practice, it is not an absolute necessity that they encounter this cost barrier. A recent study shows that "many project teams are building green buildings with little or no added cost, and with budgets well within the cost range of non-green buildings with similar programs." (Matthiessen 2007) This study compared the cost of green from three perspectives: cost of incorporating individual sustainable elements, cost of green buildings compared to buildings with similar uses, and the cost of the green building compared to the original budget. (Matthiessen 2007)

2.3 Traditional Design v. Whole-System Design

Traditional Design Strategy

Traditional design strategies utilized in engineering tend to optimize pieces of a system on an individual basis, rather than optimizing the system as a whole. This problem is two-fold. First, since it’s the only way that engineers have practiced, they typically will teach the next generation of engineers the same methods. Second, the multiple disciplines of engineering have become highly specialized, and devote little to no time towards learning how systems designed by the other disciplines operate. These methods of learning lead to projects that cross disciplines being broken down into projects specific to their discipline, designed as individual systems, and then pieced together to create the originally specified system. In doing so, the individual disciplines only consider the optimization of their piece of the system, rather than the optimization of the system as a whole.

Whole-System Design Strategy

Whole-system design takes a drastically different approach to the design process. The goal of this design strategy is to optimize the system as a whole, rather than seeking optimization benefits from key components. The result is a system that is more efficient and sustainable. While capital costs of certain components may be higher, those costs are offset by lower costs of other components as a result. Furthermore, when the system is optimized as a whole, large savings are observed in the operating costs. These reduced operating costs also indicate that less waste is being produced, and fewer resources are being utilized to complete the same work as the traditional design. With the whole-system approach, it is always encouraged to "design products and processes so that wastes from one are used as inputs to another." (CSE 2009) For instance, heat shed by the system should be recovered and utilized in another portion of the system.

2.4 Big Pipes, Small Pumps Case Study Introduction

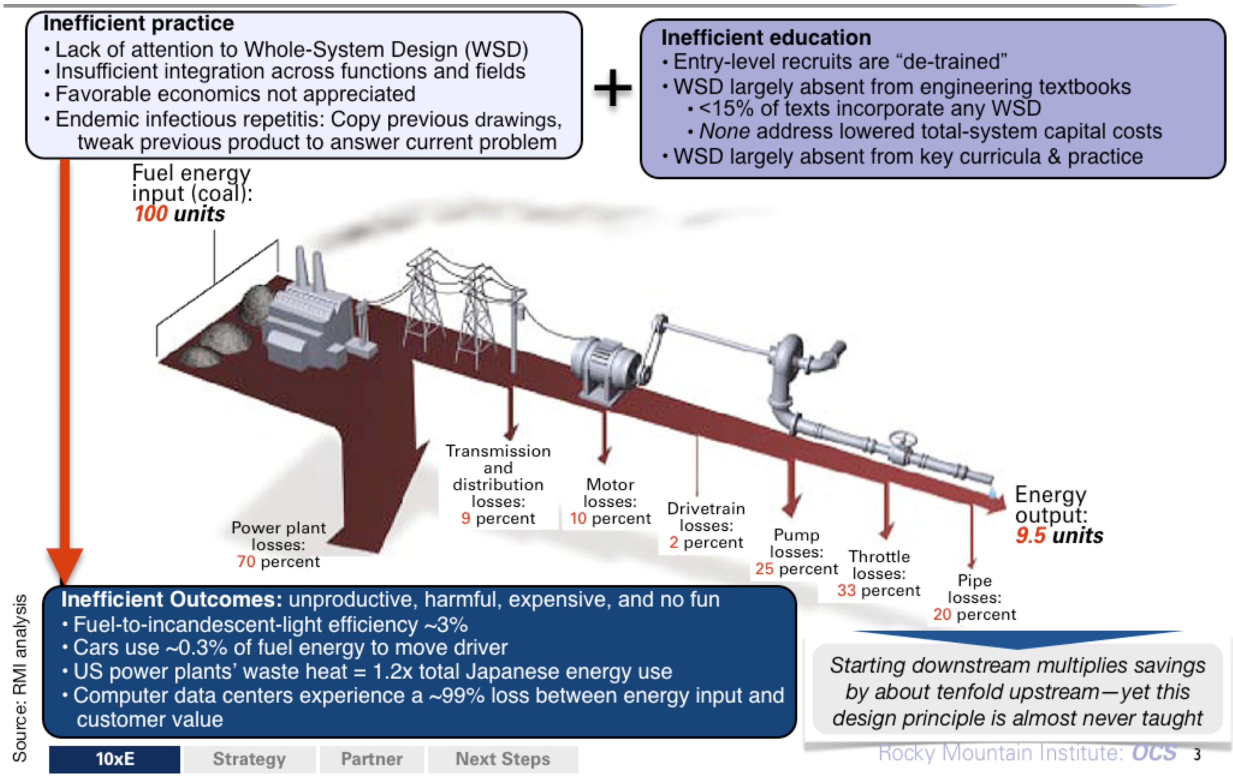
During 1997, a carpet manufacturing company was to build a new plant in Shanghai, China. The original design of the facility called for 14 pumps to be used in a runaround heat transfer loop. These original pumps would demand 70.8 kW_e of total power. After Jan Schilham of Interface/Holland reviewed the design, he reduced the total power demand by 86% to only 9.7 kW_e. While this drastic reduction in and of itself is impressive, he was also able to reduce the capital cost of project as well. (RMI)

The initial design was based on traditional design practices of placing the pumps in the facility, and then using small pipes to snake around the facility until they end up at their final destination. With this design practice, each individual piece of the system is optimized separately. While this design does accomplish the system's purpose, it does not take the efficiency of the whole-system into account, and is therefore extremely inefficient. (RMI)

The redesign was looked at from an entirely different standpoint and took into account the efficiency of the whole-system rather than only bits and pieces of it. This was done so in an attempt to make the system more energy efficient. Typically, pumps are chosen, and then pipes are routed and sized based on the specifications of the pump. However, in this case the pipes were sized to be as efficient as possible, which allowed for much smaller pumps to be utilized. Rather than using small pipes with a multitude of bends, larger pipes were utilized with fewer elbows. The larger pipes helped increase the efficiency of the system in two ways. First, the larger pipes resulted in less friction meaning that the pumps would have to work less against friction while still moving the fluids. Second, there were fewer elbows in the pipes, which also resulted in the pumps being required to work less. (RMI)

2.5 Global Effects

Whole-system designs require the use of fewer raw materials. Due to the losses incurred during the production and distribution of energy, an increase in efficiency of the end use functions in the system will result in the greatest reduction of materials used for energy production. For example, a typical industrial pumping system, as seen in Figure 2, contains so many losses that for every 100 units of fossil fuel consumed, a typical power plant will only produce enough electricity to deliver 9.5 units of flow out of a pipe. Therefore, when efficiency is gained that results in saving 10 units of energy within the pumping system, the result is more than 100 fewer units of fossil fuel and pollutants being consumed and created at the power plant. (Hawken 1999)



Inefficient practice

- Lack of attention to Whole-System Design (WSD)
- Insufficient integration across functions and fields
- Favorable economics not appreciated
- Endemic infectious repetitis: Copy previous drawings, tweak previous product to answer current problem

+

Inefficient education

- Entry-level recruits are "de-trained"
- WSD largely absent from engineering textbooks
  - <15% of texts incorporate any WSD
  - *None* address lowered total-system capital costs
- WSD largely absent from key curricula & practice

Inefficient Outcomes: unproductive, harmful, expensive, and no fun

- Fuel-to-incandescent-light efficiency ~3%
- Cars use ~0.3% of fuel energy to move driver
- US power plants' waste heat = 1.2x total Japanese energy use
- Computer data centers experience a ~99% loss between energy input and customer value

Starting downstream multiplies savings by about tenfold upstream—yet this design principle is almost never taught

Source: RMI analysis

Rocky Mountain Institute: *OCS* 3

Figure 2 – Industrial Pumping System and Associated Losses

As of 1997, the industrial sector accounted for 37% of the primary energy consumed in the United States (Interlaboratory Working Group 2000). Within this sector, motors use two-thirds of the energy consumed. This indicates that approximately 25% of the energy used in the United States is consumed by motors within the industrial sector (Southwest Energy Efficiency Project 2002).

In Figure 2, the flow of energy through a typical industrial scenario is illustrated. As indicated, the motor is the first industrial component to draw power from the grid. When whole-system design practices are used, the losses downstream of the motor are reduced drastically, resulting in smaller pumps that require less energy from the motor. Upon sufficient reduction in energy demand, smaller and smaller motors may be used, yielding a drastic decrease in energy consumption by the system as a whole.

3 RESEARCH METHOD

The research method used to establish and test a process for assessing methods to teach whole-systems design to engineering students is based on The National Academies Committee recommended method for identifying and addressing preconceptions:

I. "identification of the subject areas for study and the key concepts that students must comprehend in order to understand each subject area"
    - Addressed in Section 2 – Background and Need

II. "assessment tools that allow for a test of comprehension of these concepts, including tests of the degree to which students' understanding supports new learning (transfer), would also be developed"
    - Addressed in Section 3.2 – Determine Students' Preconceptions

III. "review of existing research that explores the preconceptions that students bring to that subject area and an extension of the research into areas that have not been adequately explored"
    - Addressed in Section 2.2 - Addressing Preconceptions
    - Addressed in Section 3.2 – Determine Students' Preconceptions

IV. "development of learning opportunities and instructional strategies that build on, or challenge, those preconceptions"

    - Addressed in Appendix A – Big Pipes, Small Pumps Case Study
    - Addressed in Section 3.1 – Identify and Develop a Case Study of an Effective Whole-System Design

V. “experimental testing of the newly developed learning tools and instructional strategies…as a measure of comprehension”

    - Addressed in Section 3.4 – Assess the Change in Preconceptions

VI. “written reports of research results, as well as descriptions of tested instructional techniques for working with student preconceptions”

    - Addressed in Sections 4-5 - Results and Conclusions

3.1 Identify and Develop a Case Study of an Effective Whole-System Design

Through working with RMI, a case study involving the redesign of a heat transfer loop at a carpet factory in Shanghai, China was developed and written by the author. This case effectively demonstrates the radical efficiency gains that are possible when whole-system design is practiced. The original design resulted in a system that consumed 70.8 kWe, whereas the whole-system design approach resulted in the same system consuming only 9.7 kWe. (RMI)

The development of the case study was completed by a team consisting of graduate students, industry professionals, and employees of RMI. Technical data was collected to determine the efficiency gains made, and exactly where in the design process these efficiency gains came from. After the technical data was compiled, the design process of the base case and the design process of the whole-system approach were compared. Once it was shown how the efficiency gains were obtained using whole-system design, example problems were constructed to be used in classroom settings.

The case study that was developed to be used during this iteration of research is presented in Appendix A, and was also used in the development of a case study to be published by RMI for distribution throughout academia.

3.2 Determine Students' Preconceptions

In order to determine to what degree the case study and aforementioned teaching methods succeed in teaching students the benefits of whole-system design, the students' preconceptions about sustainability and whole-systems design must be determined. It is felt that the most appropriate manner to determine their preconceptions is by creating a questionnaire that allows for a range of answers using a Likert Scale. By allowing a range of answers, rather than forcing them to answer yes or no, their true understanding of the material can be better understood. Once the questionnaire was completed, a sample of students was selected to conduct interviews with to attain feedback about the effectiveness of the teaching methods.

Previously, in an attempt to understand how much engineering students already know about sustainable development and to understand the knowledge gaps, Azapagic and Shallcross carried out a world-wide survey of undergraduate engineering students to determine students' level of knowledge pertaining to sustainable development (Azapagic 2005). Some preconceptions that were found during their study are: sustainable engineering is more expensive than current practices, sustainable engineering will be important in future generation but is not currently of importance, and technology will come along that will bail us out of any problems created by current engineering practices (Azapagic 2005). Their survey and its results were used as a starting point for developing the questionnaire used in this research; however, the questionnaire used in this research was original.

Questionnaire

1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree

1. Sustainable projects require greater operating cost than traditional projects.
2. Sustainable projects require greater initial (design and construction) costs than traditional projects.

3. I have a clear picture of what is meant by “sustainable construction.”
4. The nature of the design process has a huge impact on the sustainability of a project.
5. Implementing more sustainable practices on engineering projects can have a measurable impact on global issues.
6. I will have the technical ability within the next 5 years to make decisions that have a measureable impact on global issues.
7. Incremental (<20%) sustainability improvements in engineering projects and practice are possible with current technologies.
8. Drastic (>80%) sustainability improvements to engineering projects and practice are possible with current technologies.

Questions 2, 4, 6, and 8 were used as data points during this iteration of research and address the misconceptions discovered by Azapagic and Shallcross. It was important to have researched existing misconceptions that were found in previous research as a starting point, in order to ensure the best chance of obtaining valid results on the small sample size which was being surveyed during this research. Question 2 was used to measure the students’ perceptions related to the cost impact that sustainable designs have on a project. Question 4 was used to measure the students’ perceptions related to how the design process affects the sustainability of a project. Question 6 was used to measure the students’ perceptions related to how they feel they will be able to address sustainable design issues in the future. Question 8 was used to measure the students’ perceptions related to the possibility of current technologies being able to be utilized to achieve large efficiency gains. Questions 1, 3, 5, and 7 were not intended to be used as data points during this iteration of the research. Instead, they were “dummy” questions used to prevent students from anticipating the answers that were desired by the researchers, and thereby giving answers that were not in correlation with their perceptions.

3.3 Introduce the Case Study

The case study utilized must address the students’ preconceptions in a manner that reinforces correct preconceptions as well as reverses misconceptions. A proven method for implementing course material utilizing case studies is Problem-based Learning. This method of teaching guides the student to learn by giving problems that must be researched outside of the academic setting. By forcing the student to delve into research of the subject matter, they understand and retain more of the information that is initially presented. Based on this information, one research question for this project is as follows: Does problem-based learning, using a case study, address misconceptions, related to whole-system design, of general engineering students?

Problem-based learning is utilized extensively in medical and professional schools. Slowly, it is beginning to be incorporated into various other fields of study. The field of engineering education is a near perfect fit for this style of teaching that promotes the acquisition of knowledge, the acquisition of skills to continue improving one’s knowledge, and the acquisition of professional problem-solving skills. (Perrenet 2000, Rhem 1998)

Problem-based learning is based on the idea that students will work in small groups in order to solve real world problems. Rather than being spoon fed the theory, they are introduced to the basic concepts of the theory, and then the student is responsible for delving deeper into the subject matter for a greater understanding. This exploration into knowledge is promoted by presenting the work groups real world case studies as open ended engineering problems, rather than the traditional method of giving a problem that has a single defined answer. Since whole-systems design is started with a clean sheet approach, there is no singly defined answer, and problem-based learning should therefore be an appropriate method of teaching this design practice. “The primary distinction is the focus on introducing concepts to students by challenging them to solve a real world problem.” (Rhem 1998, Barrows 1996)

In utilizing problem-based learning, the goal is to produce students that will:

- *“Engage the problems they face in life and career with initiative and enthusiasm.*
- *Problem-solve effectively using an integrated, flexible and usable knowledge base.*
- *Employ effective self-directed learning skills to continue learning as a lifetime habit.*

- *Continuously monitor and assess the adequacy of their knowledge, problem-solving and self-directed learning skills.*
- *Collaborate effectively as a member of a group.” (PBLI)*

By producing these types of students, problem-based learning will also provide industry with better engineers. As time has progressed, engineers have been asked to design much more complex systems. Because of this change in design criteria, there should also be a change in teaching practices to more effectively treat these complex systems. Rather than maintaining the traditional methods of teaching, which are more tailored to older and less complex systems, problem-based learning will expose the students to the real world scenarios they will face once they graduate from academia. (Allen 2006, Lehmann 2008, Manuaba 2007)

The case will be presented to one class in a manner consistent with the practice of problem-based learning. After being introduced to the case, students will be informed of both the traditional and whole-system design philosophies. Once the students’ have a basic understanding of the design practices, they will be tasked with creating the lay out and designing a heat transfer loop using both practices. In doing so, the students will be required to search for a solution to an open ended problem by delving deeper into the subject matter outside of class. This will result in the students gaining a better understanding of the design practice and retaining more of the pertinent information presented during the lecture.

Examples of the material will also be presented to a control group in a second class using the more traditional lecture format. This will be done by presenting the students with the facts of the case study, but not having them perform the design process of the case study outside of class.

3.4 Assess the Change in Preconceptions

A period of time after completion of teaching the material, and the problem-based learning students completing related projects, the original questionnaire will be presented again to both groups of students. Also, follow up interviews with a small group of students will be performed. It is felt that by delaying the follow-up questionnaire by several weeks from the end of the material, the data collected will better represent the students' retained conceptions, rather than biasing the results by having the material fresh on their minds. The results from this round of questioning will be compared to the results from the questionnaire that is completed prior to the instruction taking place. Based on these results, it will be determined how effective the case study and teaching method is at correcting misconceptions about sustainable engineering.

3.5 Define a Method to Replicate this Study for Other Cases and Other Students' Study of Sustainable Design

In order for this research to be most beneficial, a method must be defined that is able to be both duplicated and refined during future iterations. The following is a suggested method, based on the experience gained from this iteration.

Preconceptions to be tested must first be determined. Based on the constructivist theory, to properly teach a student new material, the preconceptions of the student must be determined so that misconceptions can be properly corrected before new material is addressed. These preconceptions will also be used when deciding on the content of a case study to be used or developed. Furthermore, there must be a definitive and justifiable correct answer to the preconceptions being tested. This is necessary so that misconceptions can be identified as such, and later corrected.

After the preconceptions to be tested are selected, a case study may either be developed specifically for the research, or an existing case study could be used. A case study that covers material addressing all of the preconceptions being tested should be used in order to be most efficient with your time. There is no reason to spend time presenting a separate case study for each concept when cases are available that address multiple concepts.

A questionnaire should then be developed that accurately assesses the preconceptions of the test group. This questionnaire should be written in a manner that does not disclose the purpose of the research to the test group in order to reduce the chance of biased answers being given. The method used during this research consisted of giving the questions to be tested along with "dummy" questions that were simply used as fillers to make the purpose of the survey less obvious.

Once the results of the questionnaire are compiled, the researcher should understand the preconceptions of the students. Misconceptions should be identified, and the emphasis points of the case study to be taught should focus on these concepts. After these focal points are determined, the case should be presented to the test group in a manner consistent with problem-based learning teaching methods.

Several weeks after concluding the material, the questionnaire should be given to the test group again. This length of time is chosen to ensure that test subjects are responding based on their long term understanding of the concepts, and not based on their short term memory.

Following the final questionnaire, the numerical results of the survey can be calculated to determine if the case and teaching practices were effective in correcting misconceptions. Focus groups can also be used to attain a better understanding of the students' answers, as well as their suggestions for improving the teaching methods during future iterations.

4 RESULTS

Questions 2, 4, 6, and 8 were selected as the data points to analyze the effectiveness that the different teaching methods had on changing students' preconceptions. The questionnaire was initially given several class periods before the case study instruction began, and was given a second time several weeks after the case study had been taught. This was done in an attempt to remove any biased that may have been gained simply by giving the questionnaire immediately after the lessons, while the material was still fresh in the students' minds. By giving the questionnaire several weeks later, the results more accurately reflect the long term perceptions of the students. After data collection was completed, the answers were given the following numerical values to be analyzed using the Likert Scale: 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree. Finally, a t-test was performed using the data points to determine whether or not the change in the students' preconceptions was statistically significant. The t-test performed was an independent t-test, and the groups were not able to be randomly selected, as the classes were determined prior to the start of this study. Also, the two classes used were of different sizes, with the control class having 45 students and the test class having 55 students. Also, differing numbers of students were present when the questionnaire was given each time.

The teaching method is just as important as the concepts being tested. In order to correct misconceptions, they must be corrected in an effective manner. Only once they are corrected, can new material be effectively taught. The following is a suggested method for successfully implementing teaching practices to address the issues:

- Determine the concepts to be tested, and the correct response.
    - Give the survey questions to groups of students that will not be participating in the study, and get their feedback as to what they interpret that the question is asking. This practice should be used to ensure that the question is actually testing the concept that it is intended to test.
- Develop or review a case study involving whole-systems design.
    - A case study containing aspects that are associated with the concepts being tested should be developed in a manner appropriate to be taught in academia. A background of the project, comparison of the whole-system design to a traditional design, and the means by which efficiency gains were achieved should be determined.
- Tailor the case being taught to the concepts that were tested.
    - Determine the aspects of the case study that most directly relate to the concepts being tested. Exercises should be prepared for the students to practice principles that are associated with these

concepts. This will allow for the students to submerge themselves in the material, and will lead to higher retention rates. It is always good practice to first practice the teaching method on a small group before presenting to the entire class in order to receive feedback on positive and negative teaching practices.

- Retest the concepts several weeks after the material is presented.

4.1 Data Analysis

Question 2 - Sustainable projects require greater initial (design and construction) costs than traditional projects.

Table 1 – Sustainable projects require greater initial (design and construction) costs than traditional projects

Question 2	PBL Pre	PBL Post		Lecture Pre	Lecture Post
Strongly Disagree	0	2		1	1
Disagree	5	14		1	15
Neutral	10	11		4	4
Agree	32	20		25	18
Strongly Agree	6	2		4	1
AVG.	**3.7**	**3.1**		**3.9**	**3.1**
StDev.	**0.788**	**1.010**		**0.772**	**1.040**
p-value	**0.001**			**0.001**	

Initially, students responded to this question with an average of 3.7, strongly leaning to ‘agree,’ in the group that would eventually be taught using problem-based learning and an average of 3.9, strongly leaning to ‘agree,’ in the group that would eventually be taught using lectures. After presenting the material involving the case study, and giving the questionnaire several weeks after the material was presented, both groups responded with an average of 3.1, nearly ‘neutral.’ A t-test was performed on the data from both groups, and the shift in students’ preconceptions was proven to be statistically significant, with a p-value of 0.001 for both sets of data. Problem-based learning and lecture teaching methods were both effective in conveying the principle to students which is, sustainable designs are not inherently more expensive than traditional designs.

Question 4 - The nature of the design process has a huge impact on the sustainability of a project.

Table 2 – The nature of the design process has a huge impact on the sustainability of a project.

Question 4	PBL Pre	PBL Post		Lecture Pre	Lecture Post
Strongly Disagree	2	0		1	1
Disagree	1	0		1	0
Neutral	8	6		2	1
Agree	19	31		19	19
Strongly Agree	22	16		11	19
AVG.	**4.1**	**4.2**		**4.1**	**4.4**
StDev.	**1.000**	**0.622**		**0.880**	**0.774**
p-value	**0.655**			**0.190**	

Initially, students responded to this question with an average of 4.1, strongly leaning to 'agree', in the group that would eventually be taught using problem-based learning as well as in the group that would eventually be taught using lectures. After presenting the material involving the case study, and giving the questionnaire several weeks after the material was presented, the problem-based learning group responded with an average of 4.2, and the lecture group responded with an average of 4.4. Though there was a shift observed in the data toward 'strongly agree,' the t-test results indicated that the shift was statistically insignificant, with p-values of 0.655 and 0.190, respectively.

Question 6 - I will have the technical ability within the next 5 years to make decisions that have a measurable impact on global issues.

Table 3 – I will have the technical ability within the next 5 years to make decisions that have a measurable impact on global issues.

Question 6	PBL Pre	PBL Post		Lecture Pre	Lecture Post
Strongly Disagree	0	1		1	1
Disagree	2	4		5	3
Neutral	14	12		8	6
Agree	31	23		15	20
Strongly Agree	7	12		5	10
AVG.	**3.8**	**3.8**		**3.5**	**3.9**
StDev.	**0.711**	**0.957**		**1.020**	**0.966**
p-value	**0.962**			**0.142**	

Initially, students responded to this question with an average of 3.8, strongly leaning to ‘agree’, in the group that would eventually be taught using problem-based learning and an average of 3.5, in the middle range of ‘neutral’ to ‘agree’ in the group that would eventually be taught using lectures. After presenting the material involving the case study, and giving the questionnaire several weeks after the material was presented, the problem-based learning group responded with an average of 3.8, and the lecture group responded with an average of 3.9. There was no shift in the response of the problem-based learning group, and though there was a shift observed in the data of the lecture group toward ‘agree,’ the t-test results indicated that the shift was statistically insignificant, with p-values of 0.962 and 0.142, respectively.

Question 8 - Drastic (> 80%) sustainability improvements to engineering projects and practice are possible with current technologies.

Table 4 – Drastic (>80%) sustainability improvements to engineering projects and practice are possible with current technologies.

Question 8	PBL Pre	PBL Post		Lecture Pre	Lecture Post
Strongly Disagree	3	0		2	1
Disagree	14	17		8	7
Neutral	10	15		11	10
Agree	19	16		9	15
Strongly Agree	1	5		4	8
AVG.	**3.0**	**3.2**		**3.1**	**3.5**
StDev.	**1.030**	**0.995**		**1.100**	**1.070**
p-value	**0.467**			**0.128**	

Initially, students responded to this question with an average of 3.0, 'neutral', in the group that would eventually be taught using problem-based learning and an average of 3.1, nearly 'neutral' in the group that would eventually be taught using lectures. After presenting the material involving the case study, and giving the questionnaire several weeks after the material was presented, the problem-based learning group responded with an average of 3.2, a slight shift toward ‘agree,’ and the lecture group responded with an average of 3.5, a shift toward ‘agree.’ While both groups exhibited shifts from ‘neutral’ towards ‘agree,’ the t-test results indicated that the shift was statistically insignificant, with p-values of 0.467 and 0.128, respectively.

4.2 Candid Response Interviews

Focus groups from each of the two classes were interviewed after the questionnaire was presented to the students a second time. The primary objective of these focus groups was to better understand the following: the students’ perception of the teaching methods, the students’ perception of the effectiveness of the assignments in helping them better understand the material, the effect the case study had on their opinion of design practices, and their opinions on the effect that sustainable designs have on the cost of a project.

Students from the problem-based learning section felt that material was very open ended, and were of the opinion that this initially made the purpose of the material unclear. This group also expressed similar remarks about the assignment with which they were presented. It was their opinion that the assignment was more focused on the hydrology of the system, as opposed to practicing whole-system design principles. Despite this negative connotation of the material during its early stages, the group noted that once the case study was presented, it clarified the whole-system design strategy that was initially confusing. Furthermore, the group expressed an understanding that with proper planning during the early stages of a project, sustainable designs are more cost effective than traditional design practices.

Students from the class that was taught using the lecture approach felt that the very straight forward manner in which the material was taught was effective. By being presented the fact and numbers from multiple successful industry design examples, the students retained the principle that multiple uses should be sought from single components, and they also were encouraged to research more about the whole-system design method. Students in this section also found the assignment helpful; however, they did note that the massive number of examples and amount of data presented to them during the lectures was somewhat overwhelming. The students in lecture were not tasked with working through the real world case study, as this was the primary difference in the lecture and problem-based learning teaching methods. Furthermore, the group of students also expressed that their opinion had changed to understanding that sustainable designs can be a means of cost savings, rather than a strategy which adds cost.

4.3 Summary

Each teaching method, problem-based learning and lecturing, resulted in a statistically significant shift in students’ perception of costs related to sustainable projects. The students’ preconceptions regarding the following did not result in a statistically significant shift: the effect of the nature of the design process, their abilities to address global issues within the next five years, and current technology's ability to drastically improve the sustainability of design projects.

Students that were presented the material via the problem-based learning method were initially confused with the material and assignments, but thoroughly grasped the material after an in depth study of the case study. The students taught via lecture were able to grasp the principles of whole-system design, but not get the same in depth practice with the case study. Students from both classes retained the fact that sustainable projects are not inherently more expensive than traditionally designed projects. (Matthiessen 2007)

5 CONCLUSIONS

The objective of this research is to compare problem-based learning and lecture as methods to teach whole-systems design to engineering students. In order to determine if the teaching methods were effective, four preconceptions were tested, material was taught to address the selected concepts to a control group using traditional lecture methods and an experimental group using problem-based learning teaching methods. After concluding the teaching, the students' perceptions were tested again to determine if any misconceptions had been corrected.

Of the four concepts tested, only one exhibited a statistically significant shift in the students' perceptions. The three other perceptions that were tested did not result in a statistically significant shift. The perceptions tested related to the design process and technical ability in the near future were already in line with the correct perception. However, the perception tested that related to the possibility of drastic efficiency gains being possible with current technology was neutral and not affected by the material that was presented.

The concept that was effectively corrected, as shown by the statistically significant shift in data in the correct direction, dealt with costs associated with projects. Prior to the material being presented, the control group and experimental group each showed a heavy lean towards 'agree' about the statement, "sustainable projects require greater initial (design and construction) costs than traditional projects." However, after being presented with the material, both groups shifted toward 'neutral' when presented with the same statement.

The control group was presented with quick introductions to many projects that were redesigned using a whole-systems design approach that ultimately resulted in energy gains of at least four-fold. These design changes also resulted in a either a cheaper construction cost, or a short payback period for the increase in capital cost. By being introduced to successful applications of the whole-systems design process, the students were able to learn that sustainable designs do not inherently cost more than traditionally designed projects. (Matthiessen 2007)

The test group was presented with the general concepts of whole-systems design, followed up by completing design problems and an in depth breakdown of the case study compiled for this research. By effectively understanding the design process, the students realized that efficiency gains can be attained without the necessity of added costs.

Both groups of students tested had their misconceptions at least partially corrected when relating a projects design process to project cost; however, it cannot be concluded that either method of teaching is more effective than its counterpart in this study.

5.1 Research Limitations

While statistically significant results were obtained from one of the four concepts of this study, there are several limitations to this research. As this was the first iteration of the research, a limited control group and test group were used. The control group was a class of 45 students, and the test group was a class of 55 students.

The case study was developed with the Rocky Mountain Institute independent from the concepts being tested. In doing so, not as much emphasis as possible was placed on tailoring the case study to the conceptions being tested. Future iterations should place a greater focus on tailoring the case study being taught to the conceptions being tested.

Furthermore, this was the first iteration of this research. During future iterations, it will be possible to incorporate student feedback in the teaching methods to make them more effective. It will also be possible to generate a broader list of concepts to test, and thereby more effectively correct misconceptions.

5.2 Future Research

The option is available to continue this research on a much broader spectrum. RMI has been actively developing a broad range of case studies that focus on the success of whole-systems to be published as a text in academia. These case studies, as well as independently developed case studies that follow the 10xE principles, should be used during future iterations of this research.

During future iterations, sample groups should be integrated from other universities and various education levels. A broader range of concepts, generated from RMI’s 10xE principles, (Appendix B), should also be tested to determine areas of emphasis that are needed throughout a student’s academic career to produce engineers that are both knowledgeable of and capable of practicing whole-systems design. An ultimate goal would be to track exactly how students’ perceptions change throughout their academic career.

5.3 Research Summary

The objective of this research is to compare problem-based learning and lecture as methods to teach whole-systems design to engineering students. A case study, Section 3, exemplifying successful whole-systems design was developed in partnership with the Rocky Mountain Institute. Concepts to be tested were then determined, and a questionnaire was developed to test students’ preconceptions. A control group of students was taught using traditional lecture methods, and a sample group of students was taught using problem-based learning methods. After several weeks had passed, the students were given the same questionnaire as prior to the instruction, and the data was analyzed to determine if their preconceptions had changed. More specifically, the data was used to determine if the teaching methods were effective in correcting misconceptions. A statistically significant change in the students' preconceptions was observed in both groups on the topic of cost related to the design process. There was no statistically significant change in the students' preconceptions concerning the design process, technical ability within five years, and the possibility of drastic efficiency gains with current technologies. However, the results were inconclusive in determining that problem-based learning is more effective than lecture as a method for teaching the concept of whole-systems design, or vice versa.

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APPENDICIES

Appendix A

Big Pipes, Small Pumps Case Study

Narrative

Jan Schilham had a problem.   He was the design engineer working for the owner of a carpet and textile plant being built in Shanghai. The original design for the plant, done by a leading design firm, was going to require way too much power (70.8 kWe). A plant using this much power was going to limit profitability which had Jan's bosses breathing down his neck. On a personal level, Jan was sick to his stomach that a design he was supervising would contribute to an increase in climate change emissions.

Jan was not hopeful that he would be able to drastically reduce the power required of the plant. After all, the original design was done by a leading firm with lots of experience in plant design. Perhaps some small efficiency gains were possible, but surely nothing substantial. However, the pressure from his bosses and from his stomach made Jan look into a redesign of the plant.

It's a good thing Jan soldiered on. By taking a fresh look at the design, he reduced the total power by 86% (to 9.7 kWe). How much more did this design cost in up-front capital costs? Actually, the redesign cost less up front, not to mention the operating cost savings of $143,177 per year. Jan's redesign was sure going to make his bosses happy. Jan would also have an easier time sleeping at night, knowing his redesign had saved tons of emissions.

To put in perspective, Jan’s redesign of the plant was equivalent to designing a car that gets 300 mpg (instead of 30), and costs less to purchase.

The radical resource efficiency of Jan’s redesign illustrates key concepts of integrative whole-system design, specifically the expansion of system boundaries, taking the right steps in the right order, and using a multidisciplinary perspective. But, before we show how Jan applied these principles, some background on the original design is necessary.

The Initial Design

The purpose of a runaround heat transfer loop is to move heat from one location to another, via a fluid. The fluid is heated at a location, and pumped to its destination, where it will dump its heat for an intended purpose.

The initial design of the heat transfer loop in Shanghai was completed in much the same way as similar projects had been completed in the past. During the design phase of the facility, someone arbitrarily decides on the location of the pumps to be used in the system, with no regard to how this setup could affect the efficiency of the system as a whole. It is only after the pumps have been placed that any consideration is given to the pipe layout. Once the pump locations are finalized, a pipe network is laid out. Since the pumps were laid out at arbitrary locations at the beginning of the design, the pipes usually end up in runs that have to bend many times over long distances to avoid interferences and account for elevation changes as well as inappropriate mounting heights. Furthermore, the bends utilized to avoid the interferences are typically neat looking 90 degree elbows, which cause much more friction than gently sloping angles.

This traditional design typically optimizes the pipe size against the pumping energy cost, rather than against pumping energy plus capital cost savings. Pipe size is directly proportional to pipe cost. This simple fact results in the use of small diameter pipes when only the capital costs of a project are considered, which is the case many times during the bidding of a project. A small pipe diameter will result in cheaper pipe, but does not take into account the possibility of larger and more expensive pipe being utilized for the purpose of using a smaller and cheaper pump. This oversight is but one of the flaws in the current design practice.

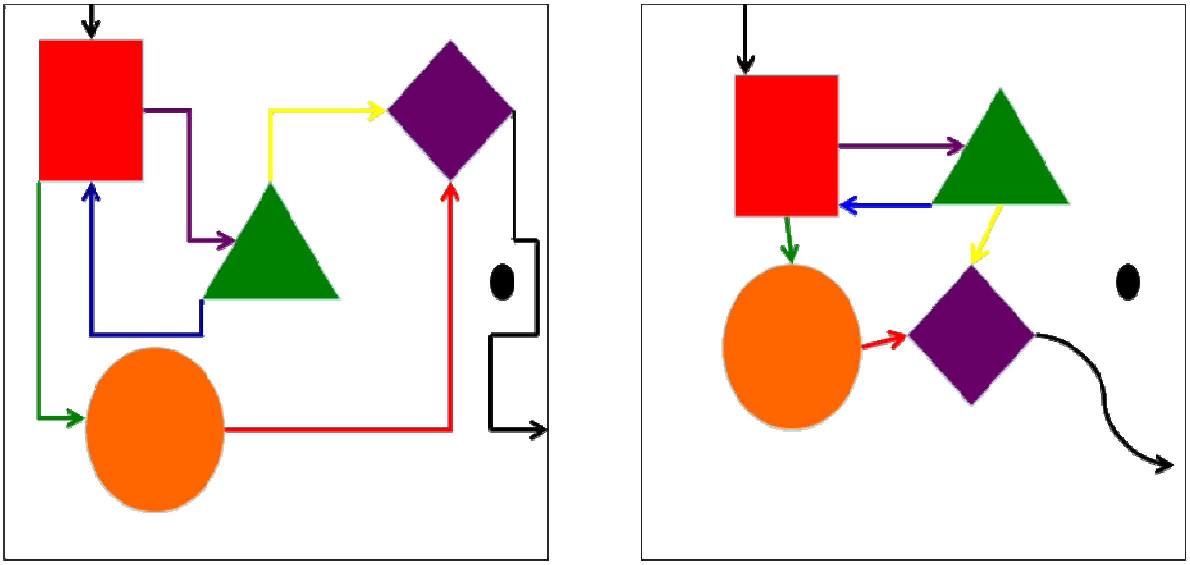
Yet another flaw in current design practices is the process in which projects are awarded. An owner will request bids for the design and construction of a facility. Typically, the main, (and in some cases the only), criteria considered to award the project is the low bid. In order to be able to give as low a bid as possible, firms will enter a project knowing that they will base the design of the facility being bid on previous designs that they have completed. This process requires the fewest number of man hours, which results in a lower bid. However, this also limits a firms’ ability to implement new design practices, even if they were to result in an eventual cost savings to the owner.

- There is an option to ask students to redesign for efficiency here prior to moving on to tell them what Jan did.

Jan's Whole-system redesign

The largest benefits of Jan's redesign came from two simple changes in design mentality, which can be seen schematically in Figure 1.

First, Jan used larger diameter pipes and smaller pumps rather than the specified small pipes and big pumps. Since friction is inversely proportional to (approximately) the fifth power of pipe diameter, making pipes 50 percent fatter will reduce friction by nearly 86 percent. Pump size (and roughly cost) will fall proportionally with the reduction in friction. With the smaller pumps being used, less energy will be consumed and the end result is a more sustainable design. The capital cost of the pipe is roughly proportional to the second power of pipe diameter. So clearly it is better to use fat pipes and small pumps. But why weren't the bigger pipes selected the first time? Traditionally pipe size is optimized against only the pumping energy cost, and pipefitters don't consider the size—and capital cost—of the pumping equipment. Optimizing the whole-system—pumping energy plus capital cost savings—yielded fat pipes, tiny pumps, and ultimately lower capital and operating costs.



Traditional Design **Big Pipes, Small Pumps Design**

Figure 1(RMI)

Second, Schilham laid out the pipes first, and then located the equipment they connect—the opposite of how systems are typically installed. Typical pipe runs twist and turn to hook up equipment that's far apart, separated by extraneous stuff, facing the wrong way, and mounted at the wrong height. This raises friction by about three- to sixfold—delighting pipefitters, who are paid by the hour, mark up the extra pipes and fittings, and don't pay for the bigger pumping equipment or electric bills. By making the pipes short and straight, the pumps, motors, and electrical components could be made even smaller and cheaper resulting in less energy consumption per pump, Figure 2.

Why are the large straight pipes so much better than small pipes with lots of bends?

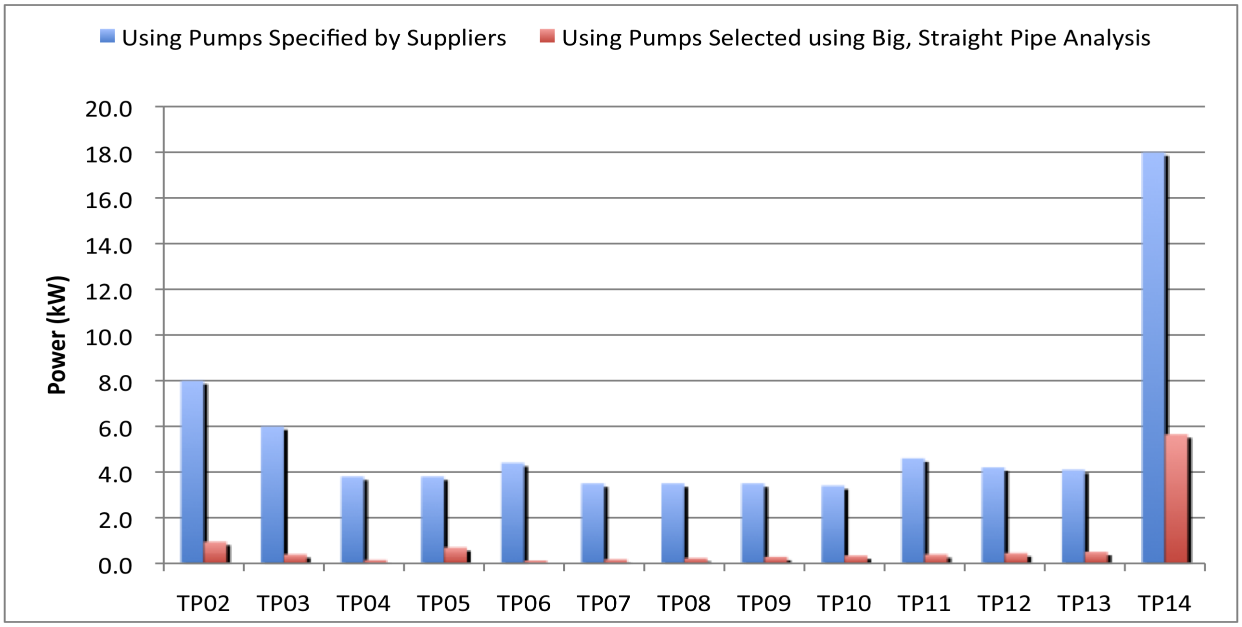


Figure 2 (RMI)

Pipe friction is caused by a variety of factors. The three factors that are easiest to control are the pipes' length, diameter, and the number of bends. The length of the pipe is directly proportional to friction losses, meaning that each time the pipe's length is reduced by half, the friction losses are also reduced by half. Also, as shown in the head loss equation earlier, each time the diameter of the pipe is doubled, the friction in the system is reduced by a factor of five (Figure 3). This aspect of the design is clearly of the greatest benefit to the overall efficiency of the system. Bends, or elbows, create varying levels of friction based on the angle and abruptness of the bend, with sharp sudden bends creating the most friction, and gradual bends creating the least friction (Figure 4). However, minimizing the number of bends should be the primary goal, with the secondary goal focusing on minimizing the angle and abruptness of the bends.

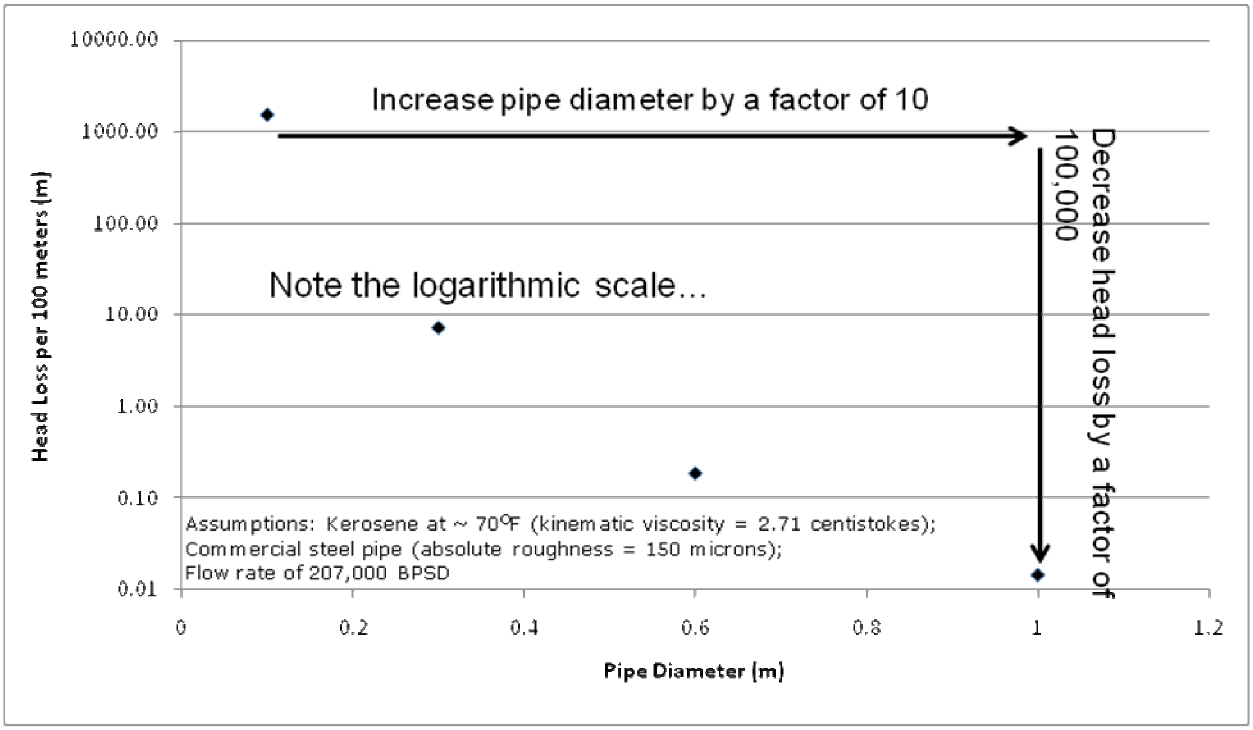


Figure 3 (RMI)

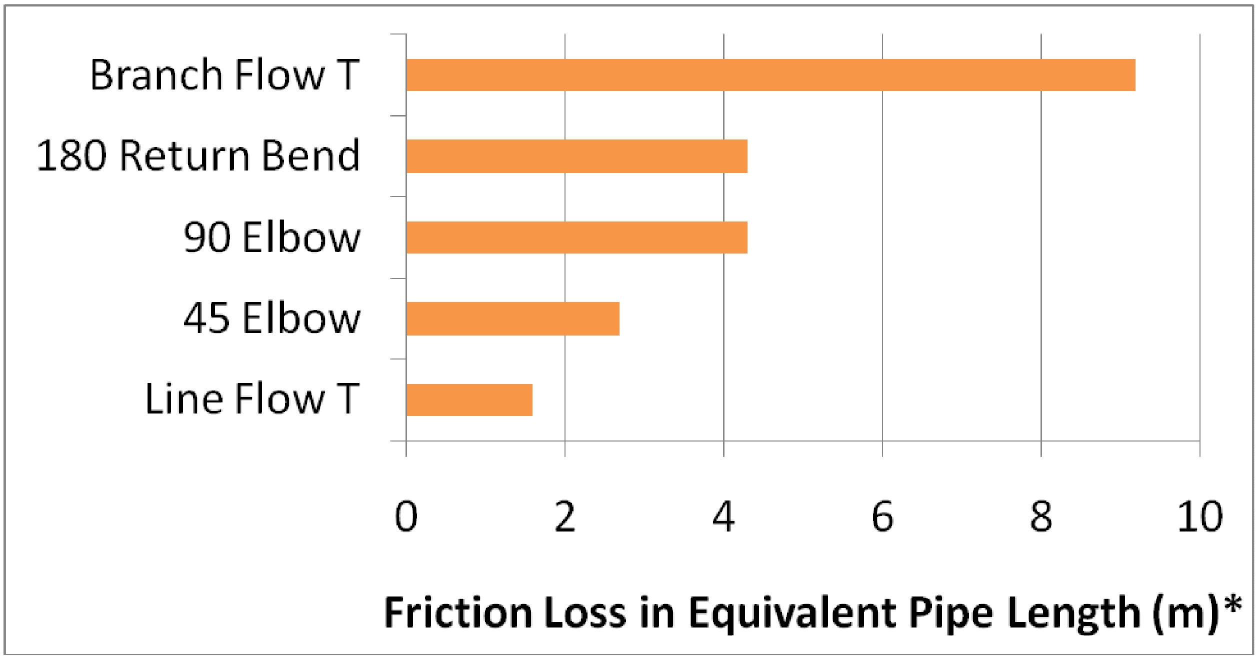


Figure 4 (RMI)

In a sense, using small pipes with lots of unnecessary bends is equivalent to driving your car with the brakes engaged the whole time; you are unnecessarily creating a great amount of friction that the engine must work to overcome in order to perform its intended task. By utilizing the larger straight pipes, Interface effectively released the brakes from the system, allowing a much smaller pump, consuming less energy, to perform the exact same task that a larger pump was going to be used to do.

Also, in addition to lower capital cost and the drastic reduction in pumping power, the redesign also yielded additional free benefits, including 70 kilowatts less heat loss via easier insulation of short, straight pipes. Other bonuses included simpler and faster construction, smaller floorspace and weight, easier maintenance access but less need for it, higher uptime, and longer life as a result of fewer erodable elbows.

Discussion Questions/Topics to Emphasize

What was the initial order of steps taken in the design?

Originally, the pumps were placed around the facility. This was followed by creating a pipe network that would eventually lead the pipes to their destinations. Because of this approach, a pipe network with many bends and an excessive length was the result. Furthermore, this resulted in large pumps being specified, and the pipe network only being optimized for the large pumps.

How did Jan reorder these steps in performing his redesign?

Rather than jumping straight into pump locations, Jan first laid out a much more efficient pipe network. To increase efficiency, he designed the pipe layout in a manner to reduce its overall length and to also reduce the number and frequency of bends or elbows. It was only after an efficient pipe layout was designed that Jan decided on the locations of the pumps. By laying out the pipe system first, Jan was able to place the pumps in locations that would create a much more efficient system, resulting in the utilization of much smaller pumps that consumed less energy.

How does this illustrate the <u>right steps in the right order</u>?

Another important general lesson to learn from this case is that the right steps need to be done in the right order. If larger pumps were selected first, and then the pipes were optimally selected and arranged, the pumps would be oversized, and the system would be inefficient. Doing things in the right order can maximize the favorable interactions between components.

How is Jan's solution more <u>multidisciplinary</u>?

As mentioned previously, the method used to design the initial system was terribly inefficient. The system was designed by focusing heavily on the capital costs of the system. Once the capital costs were determined, the individual components of the system were optimized separately for their operating costs.

There are multiple reasons as to why this current design practice is used. First and foremost, it is simply the way that has nearly always been utilized in the past. This method of thinking further reinforces the current design practice. Since engineering firms can be chosen through a low-bid process, they are essentially forced to alter and tweak previous designs of similar systems that they have performed in the past. By bidding a low cost, an engineering firm handcuffs itself from being able to try to implement a new design practice as there is only enough time and money allocated to continue to use the familiar, yet inferior, design practice.

Yet another reason that the current design practice is continuously utilized is due to a lack of communication between the engineering disciplines. For the most part, each individual discipline only thinks of its own portion of the design, with little regard as to how it could possibly effect the efficiency of other systems in the facility. However, with the recent successes that firms have had using Building Information Modeling (BIM), this could soon change. Rather than each stage of a project being designed and then passed on to the next group of engineers to add their piece to the puzzle, BIM allows all interested parties access to the same information throughout the entire design of the project. If utilized properly, BIM will allow the appropriate collaboration between engineering disciplines that will make whole-systems design a much easier process.

How are system boundaries expanded in Jan's design?

Whole-system design is far superior to the current design practice. To perform a whole-system design, the designer must take into account capital as well as operating costs of a system. Though this design process may call for higher capital costs in one area of a system, the increase will most likely lead to a lower capital cost in another area, as well as a significant reduction in operating costs.

In the case of the carpet factory mentioned earlier, larger and straighter pipes were specified in order to allow smaller pumps to be utilized. While it is true that the larger pipes used in the whole-systems design come at a higher capital cost than the small pipes used in the current design process, the large straight pipes allow for much smaller and less expensive pumps to be utilized. The reason for this reduction in pump size is due to a significant decrease of friction in the system. As can be seen in the head loss equation, $h_{loss(pipe)} = f\frac{L}{D^5}\left(\frac{8Q^2}{g\pi^2}\right)$, the two factors that are the easiest to control by the designer contribute greatly to the losses in the system. The length of the pipe is directly proportional to the friction losses. Head loss is further decreased by a factor of five for each doubling of the pipe diameter. By utilizing small pipes, with bends that create more length and more friction, the conventional design approach is unnecessarily adding a minimum of 5 times more friction to a system than the whole-systems approach. Since much smaller pumps were able to be used, the operating costs were decreased due to the decrease in energy demand of the pumps.

Appendix B – 10xE Principles

10xE Principles

Factor Ten Engineering (10xE) synthesizes, codifies, and teaches design principles whose proper application radically increases energy and resource efficiency, often at lower capital cost. These principles have been developed both independently and collaboratively by RMI and its partners. These collaborators operate in diverse communities, including engineering, architecture, manufacturing, business strategy, environmental sustainability, and others. 10xE principles can achieve very large savings in multiple sectors at many scales, across a vast range of disciplines and applications.

Whole-system design/ thinking

Whole-system design optimizes an entire system for multiple benefits, not isolated components for single benefits. This is difficult at first and takes ingenuity, intuition, and teamwork. Multiple aspects must be considered simultaneously and teased apart to reveal mutually helpful interactions.Take cars, for example. Cars are extremely complicated, so automotive engineers and designers specialize in making a component or subsystem the best it can be. The modern automobile has evolved by incremental improvements to components, with little change to the overall concept. The trouble is, optimizing isolated parts often "pessimizes" the whole: integration and synergy are lost; complexity, oversizing, and inefficiency abound. What's lacking is the big picture, the whole-system. For example, only in the past few years has a major U.S. automaker carefully examined how much lightweighting can be paid for by downsizing powertrain for the same acceleration. (Answer: much or most of it.) This is a rather basic level of design integration. More sophisticated, and rarer, is the thinking that wrings seven different functions from a single part in the front end of a Lotus Elise, or twelve from one component of a superefficient house.

10xE principles include:

Design on a clean sheet

Cultivate "beginner's mind": set aside traditional methods, assumptions, solutions, and statements of the problem. Focus on the goal and the simplest ways to reach it. Think way outside the box. There is no box. "Infectious repetitis" (copying the last set of drawings or the previous design approach) guarantees you'll get the same result—the opposite of innovation.

Think end-use

Start from the desired outcome(s): think of purpose and application before equipment. Think of mobility, not vehicles; a hole, not a drill; then ask why you wanted the mobility or the hole. End-use efficiency provides the desired service with an elegant frugality of means and unintended consequences. How much energy (or other resource), of what quality, at what scale, from what source, can do the task in the cheapest and safest way?

Start downstream

Start improving efficiency at the end-use, then work back upstream through the chain of conversions. Compounding losses, from primary energy to end-use, thereby turn into compounding savings in the other direction—savings of both energy and capital. For example, ten units of fuel into the power station to run a pump yield only one unit of flow from the pipe; therefore, each unit of flow or friction saved in the pipe can save ten units of fuel, cost, and pollution at the power station, and can make components in between (like pumps and motors) smaller, simpler, and cheaper. The same leverage applies in any chain of steps converting resources into utility: savings at any stage can be valuable, but those downstream typically offer the most leverage. Mapping the whole chain helps target improvements for greatest effect.

Design for multiple benefits

Design each element to serve multiple purposes—for example, saving both operating cost and capital cost. Is an element's function really necessary? If so, can it be done by another element (perhaps even in another system) that you're paying for anyway for other reasons? If not, could the element perform other functions too? A common sign of whole-system thinking is that every component does at least three jobs.

Do the right things in the right order

Start with fundamentals. For example, to provide comfort in a muggy climate, expand the conditions in which people feel comfortable (the building has no comfort sensation), keep heat and humidity out of the space, cool passively, then cool actively but nonrefrigeratively. The customary next step (refrigerative cooling) becomes unnecessary and uneconomic. Or to see well, improve the visual quality of the task, minimize veiling reflections and discomfort glare, optimize lighting levels, admit and control natural light, optimize electric luminaires (most people start here, on step six), then optimize controls, maintenance, and training. Similar sequences to maximize energy and money savings can be devised for practically any design task.

Choose the right size for the job

Economies of unit scale usually come with diverse but unnoticed diseconomies of unit scale. Systems usually have very different scale effects than their parts. The right size for a component is usually very wrong for the system. For example, a conventional sewage-treatment plant has standard economies of scale (~2/3 scaling law from chemical engineering), but the collection system costs many-fold more and has severe diseconomies of scale, so the right size for the whole-system is orders of magnitude smaller than conventionally supposed—and therefore should often use biological rather than chemical techniques. Micropower, by capturing 207 kinds of "distributed benefits" including the economies of mass production and rapid learning, typically beat central power plants.

Use an integrative, transdisciplinary design process

Collaborate closely among different engineering processes and disciplines throughout the design process, especially at the beginning. If necessary, intensive collaboration can be forced—as in a car design process that set requirements for the whole vehicle but not for its major systems, lest the designer of each system export her problem to the designers of the other systems. Setting requirements only at the vehicle level forced every system design leader into integrative design of the whole vehicle together, thereby spanning design silos.

Eliminate waste

Design out waste—any measurable resource use that does not create customer value. Waste consumes resources, robs attention, and requires disposal. The correct goal for any kind of waste is zero. Where waste can't be designed out or severely minimized, turn it into value: upcycle, reuse, repurpose, repair, remake, or recycle, until you're creating only value.

Start with efficiency and passive design

Design efficient systems to work unaided, harnessing natural ambient energy flows rather than consuming fuels. Smart buildings automatically keep you comfortable by embracing the conditions around them: they're climate-responsive, not climatecombating. Smart pumps sense the required flow and self-adjust to deliver it. Smart process designs default to the desired output rather than having to be continually forced into it.

Consider investments' full cost and returns

Quantify resource efficiency's financial and value returns to understand their full benefits. Include operating and capital costs plus all real side-effects (good or bad), e.g. health, safety, environment, jobs, security, satisfaction, and beauty. An overly narrow view tells you the cost of everything and the value of nothing.

Appendix C

Classroom Lesson Plan

Problem-Based Learning Class

Slides 1&2 - (5 minutes)

Students worked on example problems - (35 minutes)

Slides 5-14 with discussion where indicated – (10 minutes)

Lecture Class

Slides 1&2 – (5 minutes)

Video segments giving brief descriptions of projects with radical efficiency gains – (30 minutes)

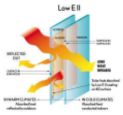
Slides 5-14 with discussion where indicated – (15 minutes)

Slide 1

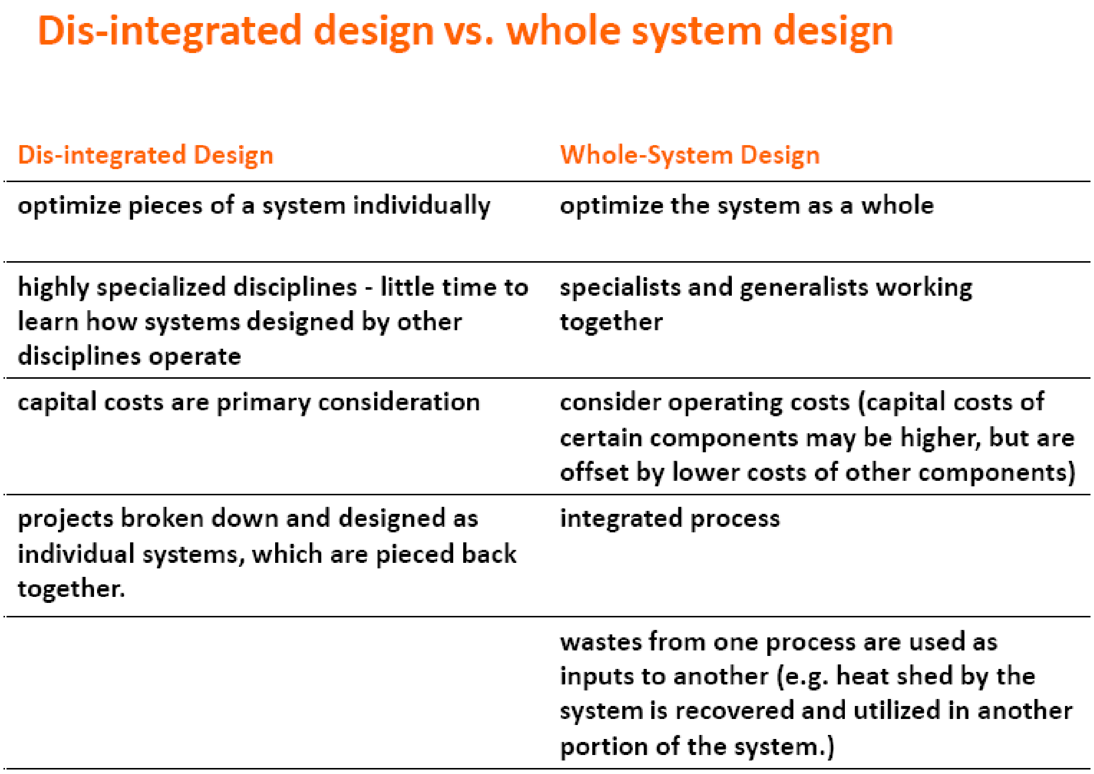
Today's learning objectives

Students will:

- **Practice "siloed" and "systems" approaches to solving engineering design problems.**



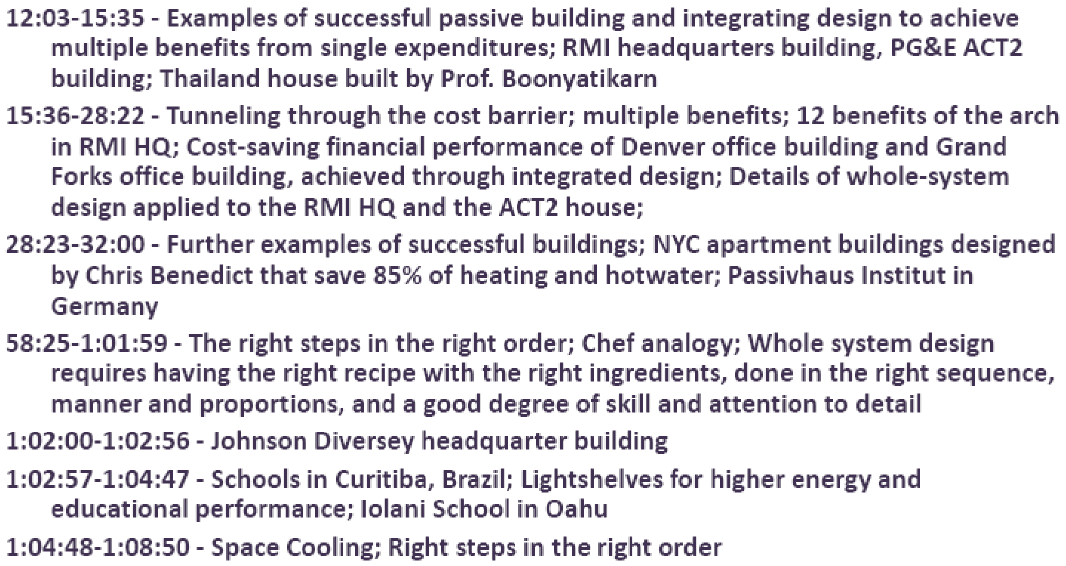
Slide 2



Dis-integrated design vs. whole system design

Dis-integrated Design	Whole-System Design
optimize pieces of a system individually	optimize the system as a whole
highly specialized disciplines - little time to learn how systems designed by other disciplines operate	specialists and generalists working together
capital costs are primary consideration	consider operating costs (capital costs of certain components may be higher, but are offset by lower costs of other components)
projects broken down and designed as individual systems, which are pieced back together.	integrated process
	wastes from one process are used as inputs to another (e.g. heat shed by the system is recovered and utilized in another portion of the system.)

Slide 3 (Video)



12:03-15:35 - Examples of successful passive building and integrating design to achieve multiple benefits from single expenditures; RMI headquarters building, PG&E ACT2 building; Thailand house built by Prof. Boonyatikarn

15:36-28:22 - Tunneling through the cost barrier; multiple benefits; 12 benefits of the arch in RMI HQ; Cost-saving financial performance of Denver office building and Grand Forks office building, achieved through integrated design; Details of whole-system design applied to the RMI HQ and the ACT2 house;

28:23-32:00 - Further examples of successful buildings; NYC apartment buildings designed by Chris Benedict that save 85% of heating and hotwater; Passivhaus Institut in Germany

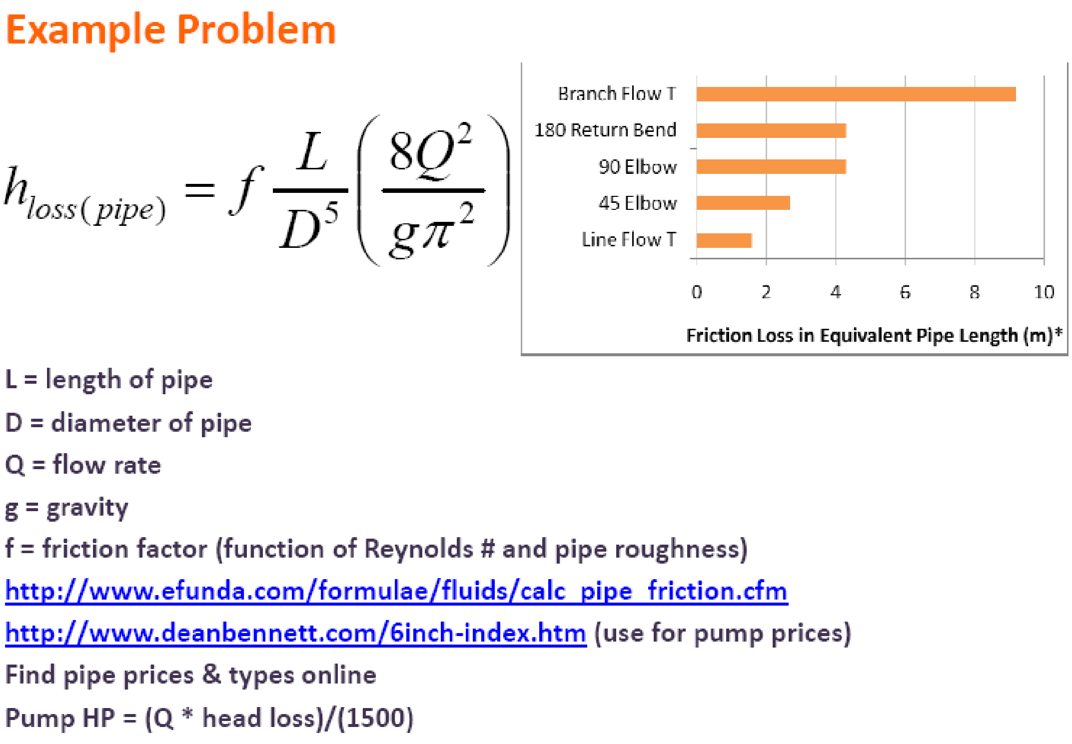
58:25-1:01:59 - The right steps in the right order; Chef analogy; Whole system design requires having the right recipe with the right ingredients, done in the right sequence, manner and proportions, and a good degree of skill and attention to detail

1:02:00-1:02:56 - Johnson Diversey headquarter building

1:02:57-1:04:47 - Schools in Curitiba, Brazil; Lightshelves for higher energy and educational performance; Iolani School in Oahu

1:04:48-1:08:50 - Space Cooling; Right steps in the right order

Slide 4 (Example Problem)



Example Problem

$$h_{loss(pipe)} = f\,\frac{L}{D^5}\left(\frac{8Q^2}{g\pi^2}\right)$$

L = length of pipe

D = diameter of pipe

Q = flow rate

g = gravity

f = friction factor (function of Reynolds # and pipe roughness)

http://www.efunda.com/formulae/fluids/calc_pipe_friction.cfm

http://www.deanbennett.com/6inch-index.htm (use for pump prices)

Find pipe prices & types online

Pump HP = (Q * head loss)/(1500)

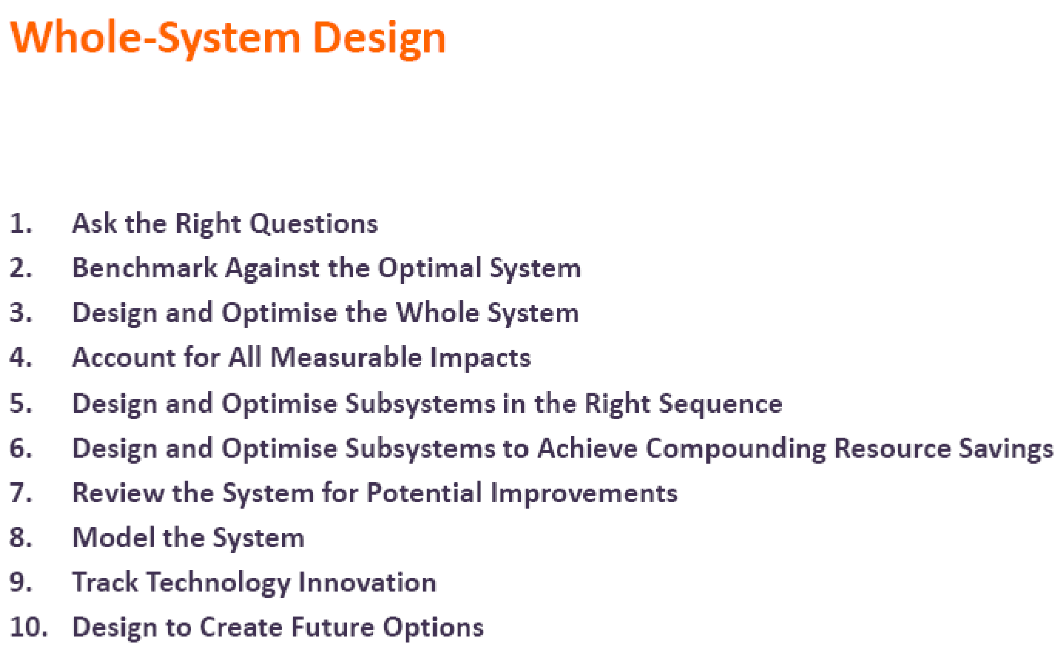
Slide 5

"Big Pipes, Small Pumps" case study

Interface

Rocky Mountain Institute

Slide 6

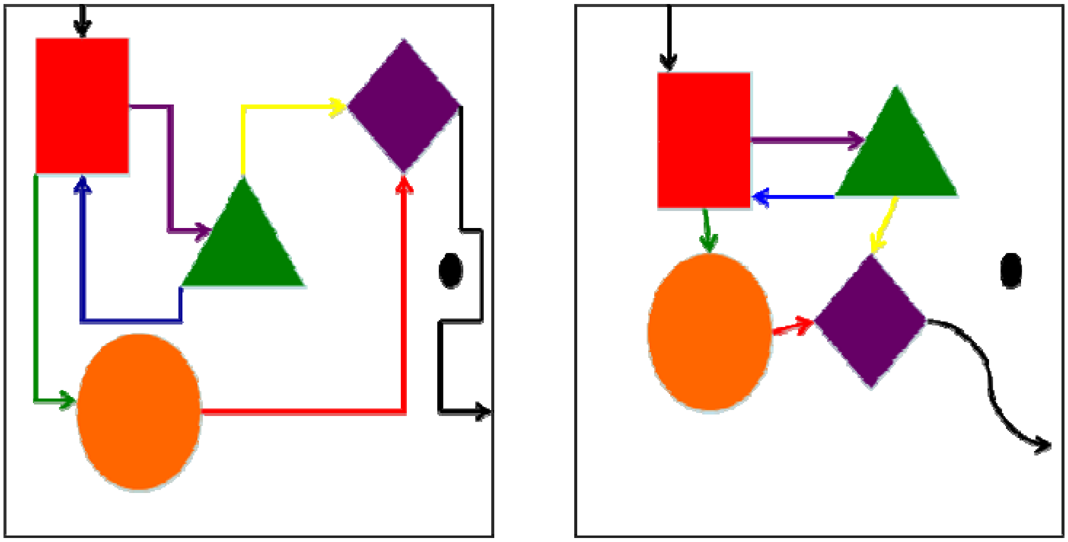


Whole-System Design

1. Ask the Right Questions
2. Benchmark Against the Optimal System
3. Design and Optimise the Whole System
4. Account for All Measurable Impacts
5. Design and Optimise Subsystems in the Right Sequence
6. Design and Optimise Subsystems to Achieve Compounding Resource Savings
7. Review the System for Potential Improvements
8. Model the System
9. Track Technology Innovation
10. Design to Create Future Options

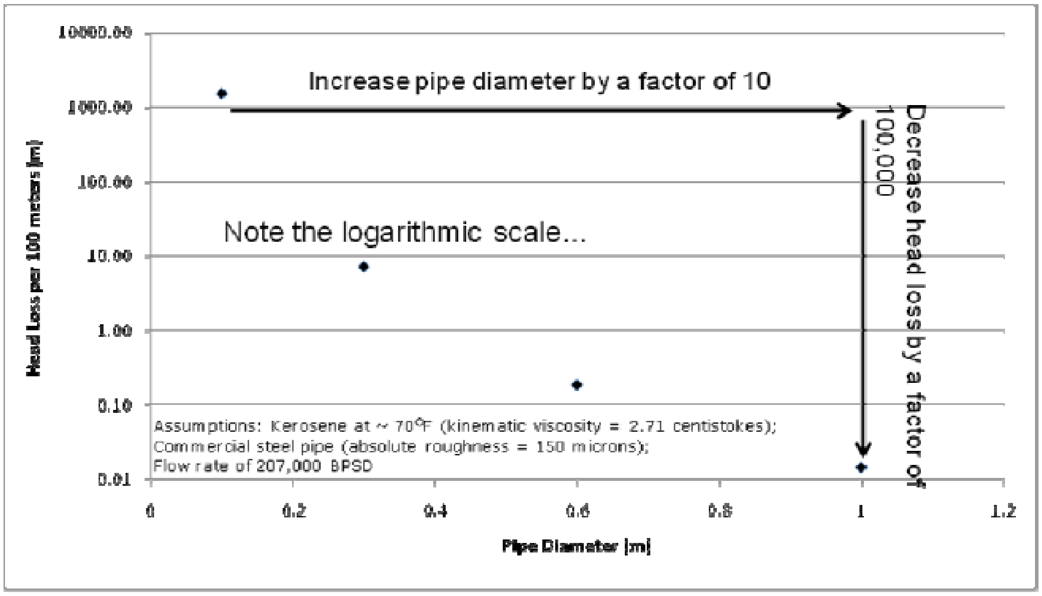
Slide 7

Fewer elbows in the pipes, which also resulted in the pumps being required to work less



Slide 8

Increased pipe diameter led to less friction meaning that the pumps would have to work less against friction while still moving the fluids.



Increase pipe diameter by a factor of 10

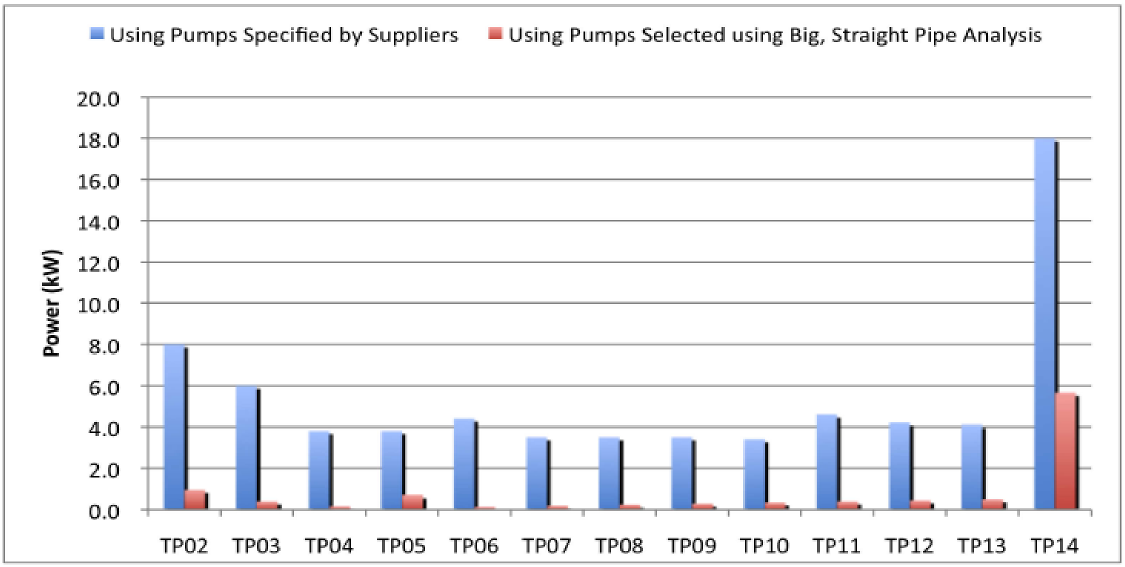
Decrease head loss by a factor of 100,000

Note the logarithmic scale…

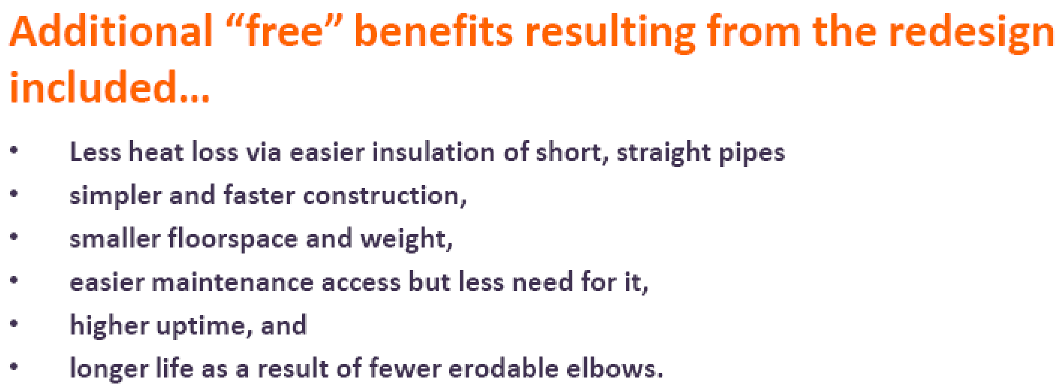
Assumptions: Kerosene at ~ 70°F (kinematic viscosity = 2.71 centistokes);
Commercial steel pipe (absolute roughness = 150 microns);
Flow rate of 207,000 BPSD

Slide 9

The original design consumed 70.8 kWe (~$62,000/yr). The whole-system redesign consumed 9.7 kWe (~$8,500/yr), an 86% reduction.



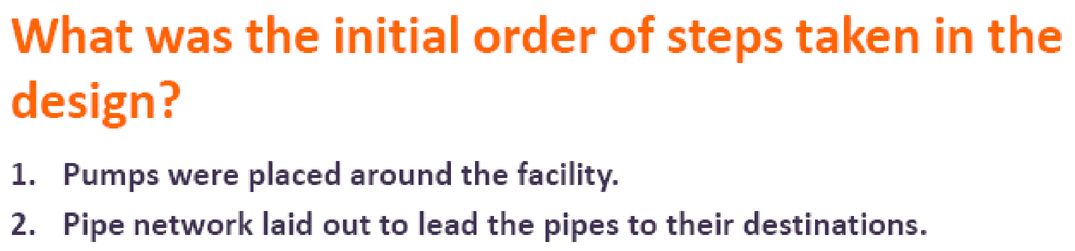
Slide 10



Additional “free” benefits resulting from the redesign included…

- Less heat loss via easier insulation of short, straight pipes
- simpler and faster construction,
- smaller floorspace and weight,
- easier maintenance access but less need for it,
- higher uptime, and
- longer life as a result of fewer erodable elbows.

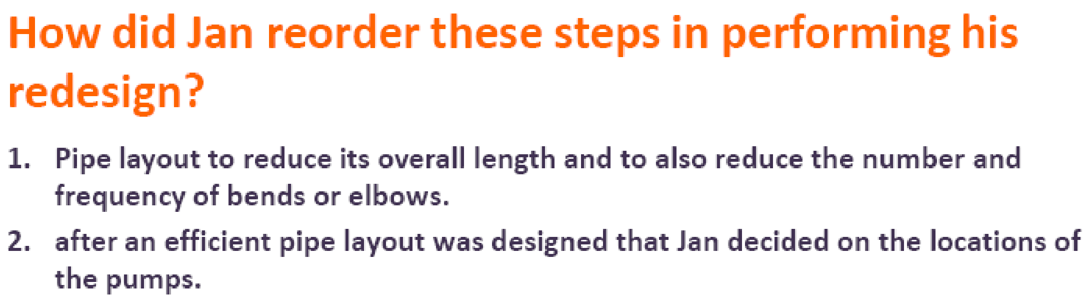
Slide 11



What was the initial order of steps taken in the design?

1. Pumps were placed around the facility.
2. Pipe network laid out to lead the pipes to their destinations.

Slide 12



How did Jan reorder these steps in performing his redesign?

1. Pipe layout to reduce its overall length and to also reduce the number and frequency of bends or elbows.
2. after an efficient pipe layout was designed that Jan decided on the locations of the pumps.

Slide 13

How is Jan’s solution more multidisciplinary?

Slide 14

How are system boundaries expanded in the redesign?

1. From capital costs only to capital and operating costs
2. From evaluation of capital costs of individual components to evaluation of costs of all components