Design Science Research in Information Systems and Software Systems Engineering

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Outline

• Design science
  – Research problems

• Design theories
  – Design research methods

• Slides at [http://wwwhome.ewi.utwente.nl/~roelw/](http://wwwhome.ewi.utwente.nl/~roelw/)
Outline

• **Design science**
  – Research problems

• **Design theories**
  – Design research methods
• Design science is the design and investigation of artifacts in context
• A.k.a engineering science,
• Technical science

Engineering science

Technical science
• Design science is the design and investigation of artifacts in context
Subjects of design science

**Problem context:**

SW components & systems, HW components & systems, Organizations, Business processes, Business roles, Services, Methods, Techniques, Conceptual structures, People, Values, Desires, Fears, Goals, Norms, Budgets, ...

**Artifact:**

SW component/system, HW component/system, Organization, Business process, Business roles, Service, Method, Technique, Conceptual structure, ...

Interaction

Something to be designed

Something to be influenced

2 september 2015

BPM
• Design science is the **design and investigation** of artifacts in context
Research problems in design science

To design an *artifact* to improve a problem *context*

Problems & Artifacts to investigate

Knowledge, Design problems

To answer knowledge questions about the *artifact* in *context*

The design researcher iterates over these two activities
Research problems in design science

To design an artifact to improve a problem context

Problems & Artifacts to investigate

Knowledge, Design problems

To answer knowledge questions about the artifact in context

- “Design a DoA estimation system for satellite TV reception in a car.”
- “Design a multi-agent aircraft taxi-route planning system for use on airports”
- “Design an assurance method for data location compliance for CSPs”
- “Is the DoA estimation accurate enough?”
- “Is this agent routing algorithm deadlock-free?”
- “Is the method usable and useful for cloud service providers?”

The design researcher iterates over these two activities
The context of design research

Design science

Improvement design  Answering knowledge questions
The context of design research

Social context:
Location of stakeholders

Goals, budgets

Design science

Improvement design

Answering knowledge questions

2 september 2015
BPM
The context of design research

Social context: Location of stakeholders

- Source of relevance.
- Relevance comes and goes

Goals, budgets

Design science

Improvement design

Answering knowledge questions

Existing problem-solving knowledge, Old designs

New problem-solving knowledge, New designs

Existing answers to knowledge questions

New answers to knowledge questions

Knowledge context:

- Source and destination of theories
- Theories are forever

Mathematics, social science, natural science, design science, design specifications, useful facts, practical knowledge, common sense, other beliefs
Outline

• Design science
  – Research problems
• Design theories
  – Design research methods
Two kinds of research problems

• Design problems
• Knowledge questions
Template for design problems

- Improve **<problem context>**
- by **<treating it with a (re)designed artifact>**
- such that **<artifact requirements>**
- in order to **<stakeholder goals>**

- *Reduce my headache*
- *by taking a medicine*
- *that reduces pain fast and is safe*
- *in order for me to get back to work*
Template for design problems

- Improve <problem context>
- by <treating it with a (re)designed artifact>
- such that <artifact requirements>
- in order to <stakeholder goals>

- Reduce my headache
  - by taking a medicine
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Stakeholder language: Problem context and stakeholder goals.
Template for design problems

- Improve <problem context>
- by <treating it with a (re)designed artifact>
- such that <artifact requirements>
- in order to <stakeholder goals>

- *Reduce my headache*
  - *by taking a medicine*
  - *that reduces pain fast and is safe*
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Technical language: Artifact and its desired properties.
Template for design problems

- Improve <problem context>
- by <treating it with a (re)designed artifact>
- such that <artifact requirements>
- in order to <stakeholder goals>

- Reduce my headache
- by taking a medicine
- that reduces pain fast and is safe
- in order for me to get back to work

- Improve the course admin
- By integrating with student admin
- Such that less data need be entered
- In order to reduce workload
A problem in science communication

• Design problems are usually not considered to be research problems

• They are stated in the form of questions
  – *How to plan aircraft taxi routes dynamically?*
  – *Is it possible to plan aircraft routes dynamically?*
  – *Etc.*

• This way, stakeholders, goals, and requirements stay out of the picture!
Engineering cycle (a.k.a. regulative cycle)

Legend: Knowledge questions? Actions!

Design implementation
• Stakeholders? Goals?
• Conceptual problem framework?
• Phenomena? Causes? Effects?
• Effects contribute to Goals?

Implementation evaluation = Problem investigation
• Specify requirements!
• Requirements contribute to goals?
• Available treatments?
• Design new ones!

Design validation
• Context & Artifact → Effects?
• Effects satisfy Requirements?
• Trade-offs for different artifacts?
• Sensitivity for different Contexts?
Implementation (transfer to problem context)
is not part of research if the problem context is society

Implementation evaluation = Problem investigation

- Stakeholders? Goals?
- Conceptual problem framework?
- Phenomena? Causes? Effects?
- Effects contribute to Goals?

Design implementation

• Stakeholders? Goals?
• Conceptual problem framework?
• Phenomena? Causes? Effects?
• Effects contribute to Goals?

Design validation

• Context & Artifact → Effects?
• Effects satisfy Requirements?
• Trade-offs for different artifacts?
• Sensitivity for different Contexts?

Treatment design

• Specify requirements!
• Requirements contribute to goals?
• Available treatments?
• Design new ones!
By default, the problem context of a research project is society

• Research projects may focus on
  – Implementation evaluation
  – Problem investigation
  – Treatment design and validation
Research problems in design science

To design an artifact to improve a problem context

Problems & Artifacts to investigate

Knowledge, Design problems

To answer knowledge questions about the artifact in context
Knowledge questions in (any) science

• Descriptive questions:
  – What happened?
  – When?
  – Where?
  – What components were involved?
  – Who was involved?
  – etc.

• Explanatory questions:
  – Why?
    • What has caused the phenomena?
    • Which mechanisms produced the phenomena?
    • For what reasons did people do this?
• Descriptive question: What is the performance of this program?
  – Execution time for different classes of inputs
  – Memory usage
  – Accuracy,
  – Etc. etc.

• Explanatory question: Why does this program have this performance?
  1. Cause: because it received this input (and not another input)
  2. Mechanism: because it has this architecture with these components
  3. Reasons: Because users use it for tasks for which it was not intended
Effect questions

– Central effect question
  • **Effect question:** Context X Artifact $\rightarrow$ Effects?
  • Descriptive or explanatory

– Generalizations
  • **Trade-off question:** Context X *Alternative artifact* $\rightarrow$ Effects?
  • **Sensitivity question:** *Other context* X artifact $\rightarrow$ Effects?
  • Descriptive or explanatory
Contribution questions

– Preliminary questions:
  • **Stakeholder question**: Who are the stakeholders?
  • **Goal question**: What are their goals?
  • Descriptive or explanatory

– Central contribution question:
  • **Contribution question**: Do Effects contribute to Stakeholder goals?
  • Descriptive or explanatory
Example knowledge questions

• **Effect:**
  – What is the execution time of the DoA algorithm?
  – What is its accuracy?

• **Trade-off:**
  – Comparison between algorithms on these two variables
  – Comparison between versions of one algorithm

• **Sensitivity:**
  – Assumptions about car speed?
  – Assumptions about processor?

• **Stakeholders:**
  – Who are affected by the DoA algorithm?

• **Goals:**
  – What are their goals?

• **Contribution evaluation (after DOA algorithm is in use)**
  – How well does the DoA algorithm contribute to these goals?
Societal implementation (transfer to societal problem context) is not part of research

**Design implementation**
- After the artifact is implemented, we can ask this question
  - Stakeholders? Goals?
  - Conceptual problem framework?
  - Phenomena? Causes? Effects?
  - Effects contribute to Goals?

**Implementation evaluation = Problem investigation**

**Design validation**
- Before it is implemented, we must ask these questions
  - Context & Artifact \(\rightarrow\) Effects?
  - Effects satisfy Requirements?
  - Trade-offs for different artifacts?
  - Sensitivity for different Contexts?

**Treatment design**
- Specify requirements!
- Requirements contribute to goals?
- Available treatments?
- Design new ones!

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2 september 2015
Outline

• Design science
  – Research problems

• Design theories
  – Design research methods
Empirical research

- The goal of empirical research is to develop, test or refine theories
- We never start empty-handed
• A **theory** is a belief that there is a pattern in phenomena
  – Speculations
  – Opinions
  – Ideologies
  – ...

• A **scientific** theory is a theory that
  – Has survived tests against experience
  – Has survived criticism by critical peers

• All theories about the real world are fallible
The structure of scientific theories

1. **Conceptual framework**
   - Constructs to frame, describe, specify, analyze, generalize about phenomena
   - Descriptions can be case-based or sample-based

2. **Generalizations** about patterns in phenomena
   - Statements that explain phenomena.
   - Explanations can be causal, architectural, or rational
   - Scope.
The structure of

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The structure of design theories

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   – Constructs to frame, describe, specify, analyze, generalize about *artifacts in context*
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The structure of design theories

1. Conceptual framework
   - Constructs to frame, describe, specify, analyze, generalize about *artifacts in context*
   - Descriptions can be case-based or sample-based

2. Generalizations about patterns in phenomena
   - Statements that explain *interactions between artifact and context.*
   - Explanations can be causal, architectural, or rational
   - Scope.
The functions of scientific theories

• To **analyze** a conceptual structure
• Use a conceptual structure to **describe** phenomena

• Use generalizations to **explain** phenomena or
• to **predict** phenomena
The functions of scientific theories

• To **analyze** a conceptual structure
• Use a conceptual structure to **describe** phenomena

• Use generalizations to **explain** phenomena or
• to **predict** phenomena
• Some phenomena can be explained but could not be predicted
  – Outcome of elections
  – Outcome of organizational change
  – Diseases

• Some phenomena can be predicted without explanation
  – Performance parameters of a machine
  – The weather

• Designers need at least the ability to predict A & C → E
Statistical theories

• Statistical conceptual framework:
  – Population, variables
  – Probability distributions over the population

• Explanations are causal, causality is difference-making.
  – If a change in X on the average results in a change in Y, then X on the average causes Y.
  – There is an average difference in Y, which can only be attributed to the average difference in X.

• Examples:
  – DOA descriptive theory: e.g. performance graphs
  – DOA causal theory: e.g. change in angle of incidence causes change in phase difference
  – Causal theory of agile software development: Introduction of agile development causes customer satisfaction to increase
History of statistical conceptual structures

- Statistical conceptual frameworks are used in
  - Social sciences: human populations
  - Physics: statistical mechanics
  - Biology: populations of animals, plants
  - Psychology: groups of people
  - Information systems: populations of organizations
  - Empirical software engineering: populations of projects, software engineers

 1800 • Population-based statistics (descriptive, including regression)

1900 • Sample-based statistics (statistical inference)

2000 • Very large sample (population)-based statistics
• In the field, the causal influence of X on Y may be swamped by many other causal influences.
  – Lab research (controlled) versus field research (almost no control)
  – Scaling up to practice
Architectural theories

• Architectural conceptual framework
  – Components, capabilities
  – Interactions among components

• Explanations are architectural
  – Phenomenon Y occurred because components C1, ..., Cn interacted in this way (technical, social, psychological, biological mechanism)
  – Rational explanations: Actor A did this because A had this goal

• Examples:
  – *DOA mechanistic theory*: e.g. input-output relation is explained by structure of the algorithm
  – *In agile development for SME, the SME does not put customer on-site, because SME resources are limited and focus is on business.*
  – *Introduction of change control board reduces requirements creep.*
History of architectural conceptual structures

• This kind of structure is used in
  – The engineering disciplines: Renaissance machines
  – Astronomy: architecture of solar system; math description
  – Physics: forces among physical bodies
  – Biology: structure and mechanisms in the body
  – Chemistry: composition and mechanisms of combustion
  – Sociology: structure and mechanisms of society, organizations,
  – Psychology: cognitive mechanisms
  – Economy: structure and mechanisms of markets
  – Sociology, economy, computer science, Structure & mechanisms of networks and games
• In the field, different mechanisms may interfere, to give unpredictable result (but explainable in individual cases).
  – Lab research versus field research
Hybrid theories

• Investigate a sample (statistical), analyze a few cases in the sample in-depth (architectural)

• Investigate a case (architectural), do a survey within the case (statistical)
Outline

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  – Design research methods
Empirical research

- The goal of empirical research is to develop, test or refine theories

Prior beliefs:
- Theories
- Specifications
- Experiences
- Lessons learned

Knowledge questions

Empirical research

Posterior beliefs:
- Updated theories
Checklist questions about research context

1. Improvement goal?
2. Knowledge goal?
3. Current knowledge?

• A research paper should answer all questions in the checklist.
Data analysis
12. Data?
13. Observations?
14. Explanations?
15. Generalizations?
16. Answers?

New research problem

Research execution
11. What happened?

Research problem analysis
4. Conceptual framework?
5. Research questions?
6. Population?

Empirical cycle

Source of rigor

Validation
7. Validity of Object of study?
8. Validity of treatment specification?
9. Validity of measurement specification?
10. Validity of inference design?

Research & inference design
7. Object of study?
8. Treatment specification?
9. Measurement specification?
10. Inference?
Research problem analysis
4. Conceptual framework?
5. Research questions?
6. Population?

Data analysis
12. Data?
13. Observations?
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16. Answers?

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Empirical cycle

Source of rigor

Validation
7. Validity of Object of study?
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Research & inference design
7. Object of study?
8. Treatment specification?
9. Measurement specification?
10. Inference?

New research problem

Research setup
The empirical research setup

• Example
  – Validating a new enterprise architecture design method
  – Validating a new model-based software testing method & tool
  – .....
Four kinds of inference

- All inferences are fallible. **Validity** is degree of support for the inference.
Case-based inference

• Describe, explain, generalize
Case-based inference

1. **Descriptive inference:** Describe the case observations.
   - Discuss *descriptive validity*.
   - *In a study of a global SE project, describe the organizational structure and communication & coordination processes based on data obtained from project documents, interviews, email and chat logs.*

2. **Abductive inference:** Explain the observations architecturally and/or rationally.
   - Discuss *internal validity*.
   - *Explain reduction of rework by the capabilities of the cross-functional team in the project.*

3. **Analogic inference:** Assess whether the explanations would be true of architecturally similar cases too.
   - Discuss *external validity*.
   - *Reason that similar teams will produce similar effects, other things being equal.*
Case-based reasoning should be architectural

- Architecture gives a basis for generalization by analogy
Sample-based inference

- Describe, aggregate, explain, generalize
Sample-based inference

1. **Descriptive inference:** Describe sample statistics.
   - Discuss descriptive validity.
   - *In an experiment with a new programming technique, describe average
     errors in treatment and control groups of students.*

2. **Statistical inference:** Infer a statistical model of the population.
   - Discuss conclusion validity.
   - *Estimate a confidence interval of difference of averages in population.*

3. **Abductive inference:** Explain the model causally or architecturally
   - Discuss internal validity.
   - *Argue that difference is caused by difference in technique. Explain by
     psychological mechanisms.*

4. **Analogic inference:** Assess whether the statistical model and its
   explanation would be true of architecturally similar populations
   - Discuss external validity.
   - *Argue that same effect will be obtained in (junior) practitioners.*
<table>
<thead>
<tr>
<th>No treatment  (observational study)</th>
<th>Case-based inference</th>
<th>Sample-based inference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observational case study</td>
<td>Survey</td>
</tr>
<tr>
<td>Treatment (experimental study)</td>
<td>Single-case mechanism experiment, Technical action research</td>
<td>Statistical difference-making experiment</td>
</tr>
</tbody>
</table>
• If all population elements were identical, statistical inference would not be needed
Sciences of the middle range

Generalization

Universal generalization

Existential generalization

Case description

Basic sciences
Physics, Chemistry, parts of Biology

Special sciences (about the earth):
Biology, Psychology, Sociology, ...

Applied sciences:
Astronomy, Geology, Meteorology, Political sciences, Management science, ...

Design sciences:
Software engineering, Information systems, Computer sciences, Electrical engineering, Mechanical engineering, ...

Case research:
Engineering, Consultancy, Psychotherapy, Health care, Management, Politics, ...

Idealized conditions
Realistic conditions
Conditions of practice

Realism
Take-home

• Design science
  – Design problems and knowledge questions

• Design theories
  – Effects of artifact in context

• Design research methods
  – Case-based and sample-based research
  – Architectural and statistical reasoning
  – Scaling up from lab to practice
Further reading


