東京大学大学院工学系研究科
SCHOOL OF ENGINEERING
THE UNIVERSITY OF TOKYO

DEPARTMENT OF
SYSTEMS INNOVATION

Systems Engineering and the V-Model:

Lessons from an Autonomous Solar Powered Hydrofoil

Joshua Sutherland, Haruya Kamiyama,
Kazuhiro Aoyama & Kazuya Oizumi

The 12th International Marine Design Conference (IMDC)
11-14 May 2015

Abstract

- **Case study: Student project** to **design**, **build** and **race** an **automatous solar powered** boat
- Development activities **analyzed** by:
  - Four **V-Model** views
- **Alternative** development **strategy** is **proposed**
- **Insight into the challenges** of systems development

Presentation Overview

1. Definitions:
   1. SolarBoat
   2. Systems Engineering
2. SolarBoat 2014 results
3. V-Model to analyse development and determine alternative work
4. Grouping solutions and building a new development plan
5. Conclusions

Presentation Overview

1. **Definitions:**
   1. **SolarBoat**
   2. **Systems Engineering**
2. SolarBoat 2014 results
3. V-Model to analyse development and determine alternative work
4. Grouping solutions and building a new development plan
5. Conclusions

SolarBoat challenge

- Lake Biwa (Japan) competition rules:
  - Max 2m^2 of solar panels
  - Max 20Wh of lead based batteries for power train
  - Complete the 20km course autonomously
  - Possibility to repair boat on route

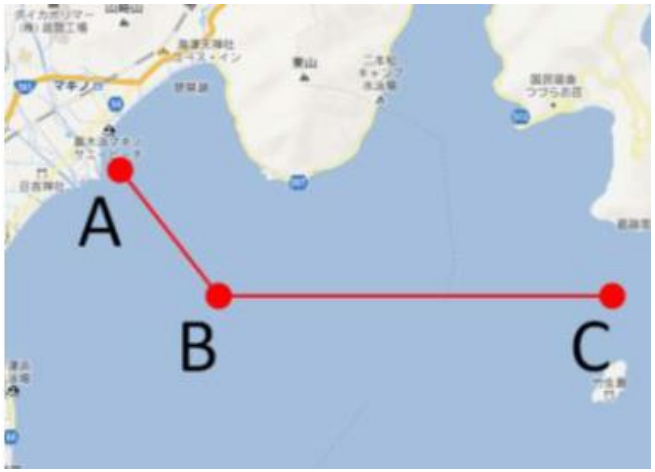


Image from: Frithiof et al. 2013

- Video (4:30 ->)

SolarBoat project attributes

- **Interdisciplinary**:
  - Engineering: Mechanical, Electrical, Software, Control, Structural, Naval
  - Operations: Design, Manufacturing, Testing, Logistics
- **Complete problem:**
  - Concept to production to operation
- **Providing a quality product that meets the user needs:**
  - To win an interuniversity competition
  - Learn about naval systems

Definitions from the International Council of Systems Engineering (INCOSE)

- **Systems Engineering** is an **interdisciplinary** approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the **complete problem**: Operations, Cost & Schedule, Performance, Training & Support, Test, Disposal and Manufacturing.
- **Systems Engineering** integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from **concept to production to operation**. Systems Engineering considers both the business and the technical needs of all customers with the goal of **providing a quality product that meets the user needs**.

INCOSE, “INCOSE - What is System Engineering?,” 14-Jun-2004.

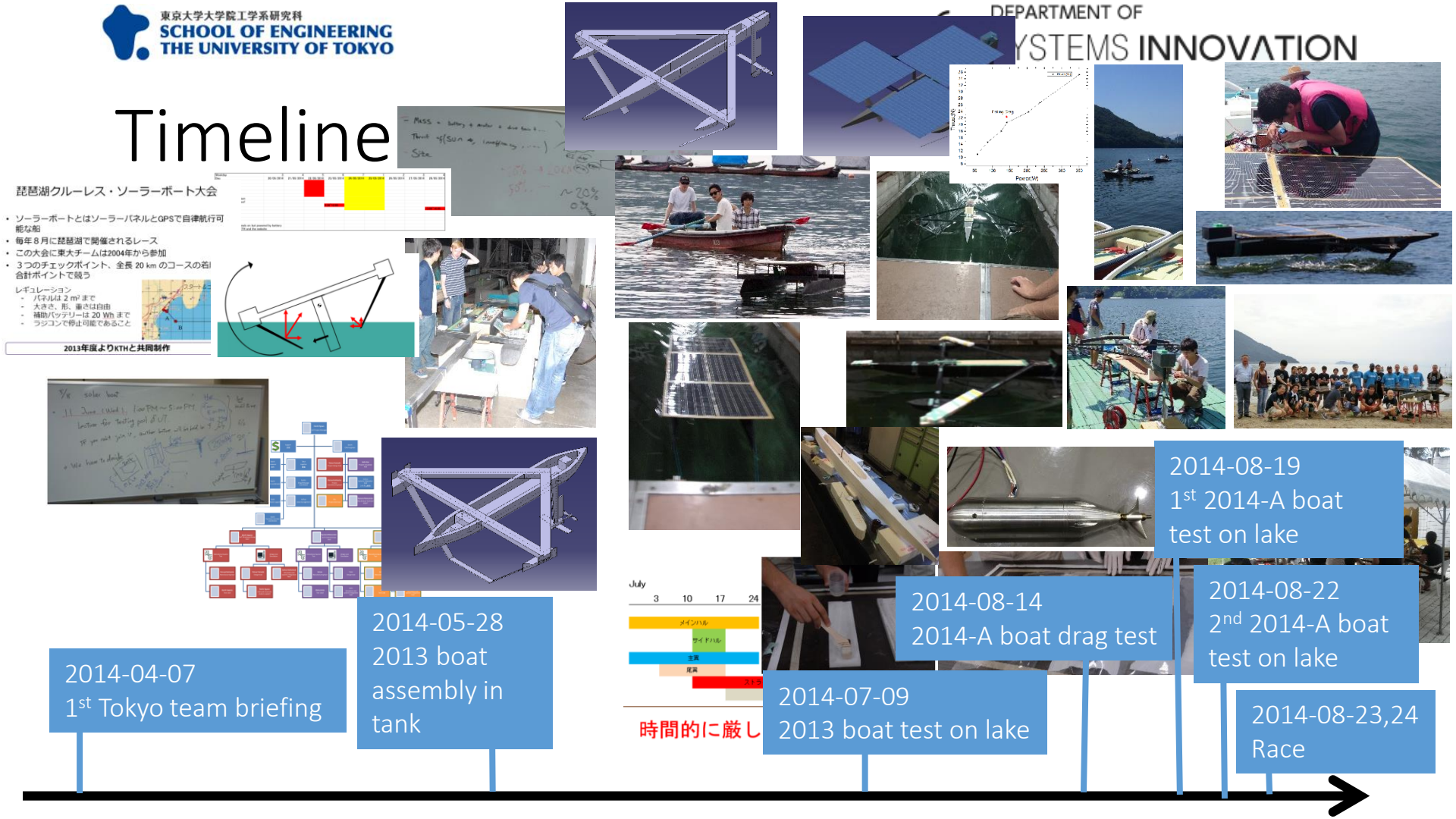
Presentation Overview

1. Definitions:
   1. SolarBoat
   2. Systems Engineering
2. **<u>SolarBoat 2014 results</u>**
3. V-Model to analyse development and determine alternative work
4. Grouping solutions and building a new development plan
5. Conclusions

東京大学大学院工学系研究科
SCHOOL OF ENGINEERING
THE UNIVERSITY OF TOKYO

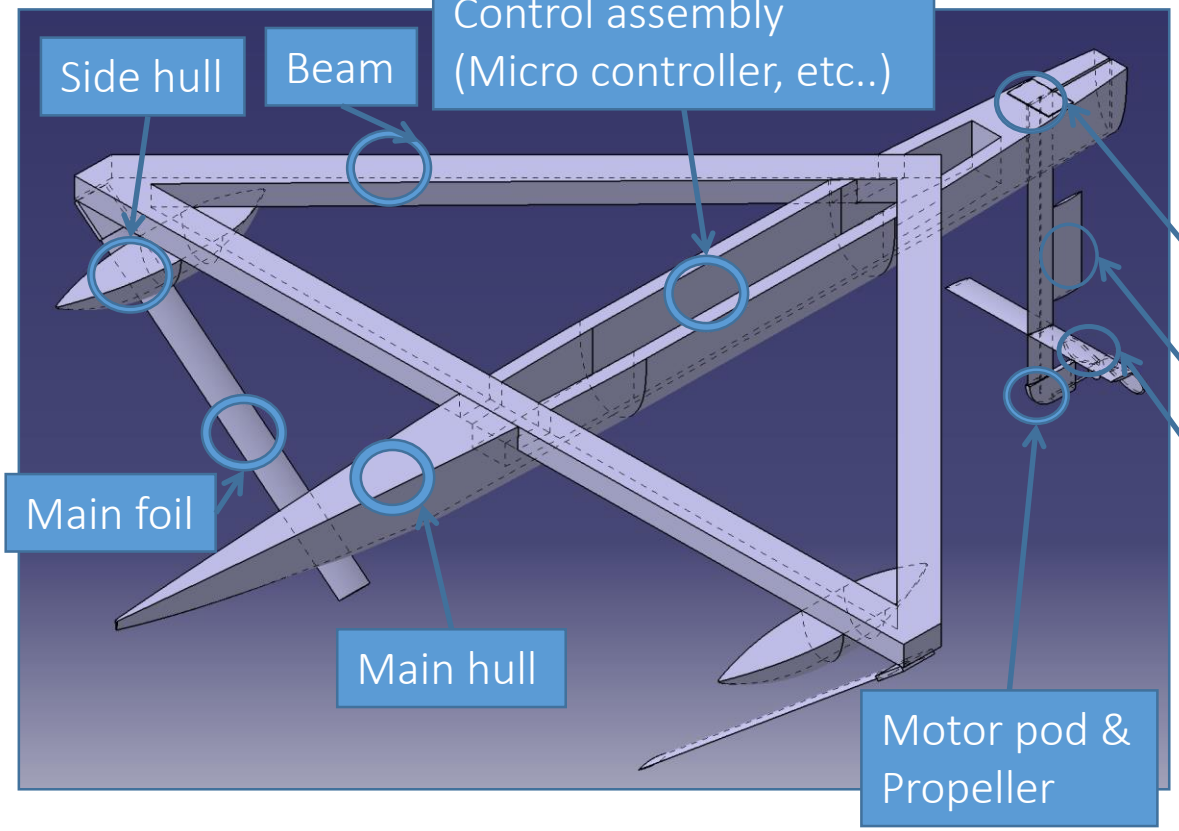
DEPARTMENT OF
YSTEMS INNOVATION

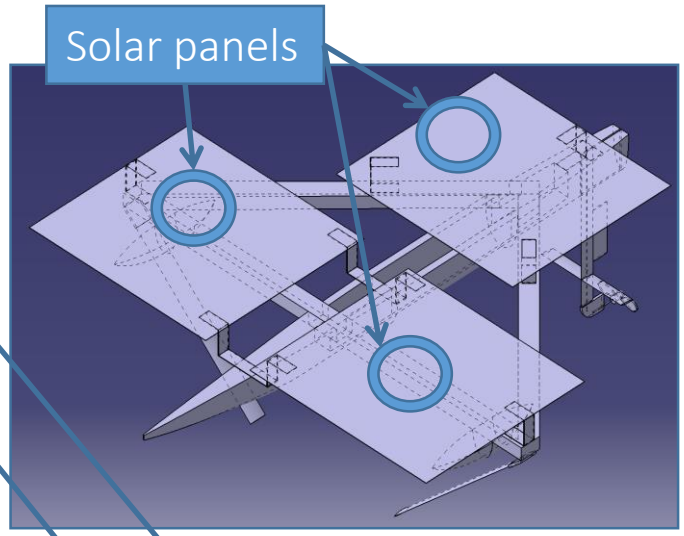
Timeline



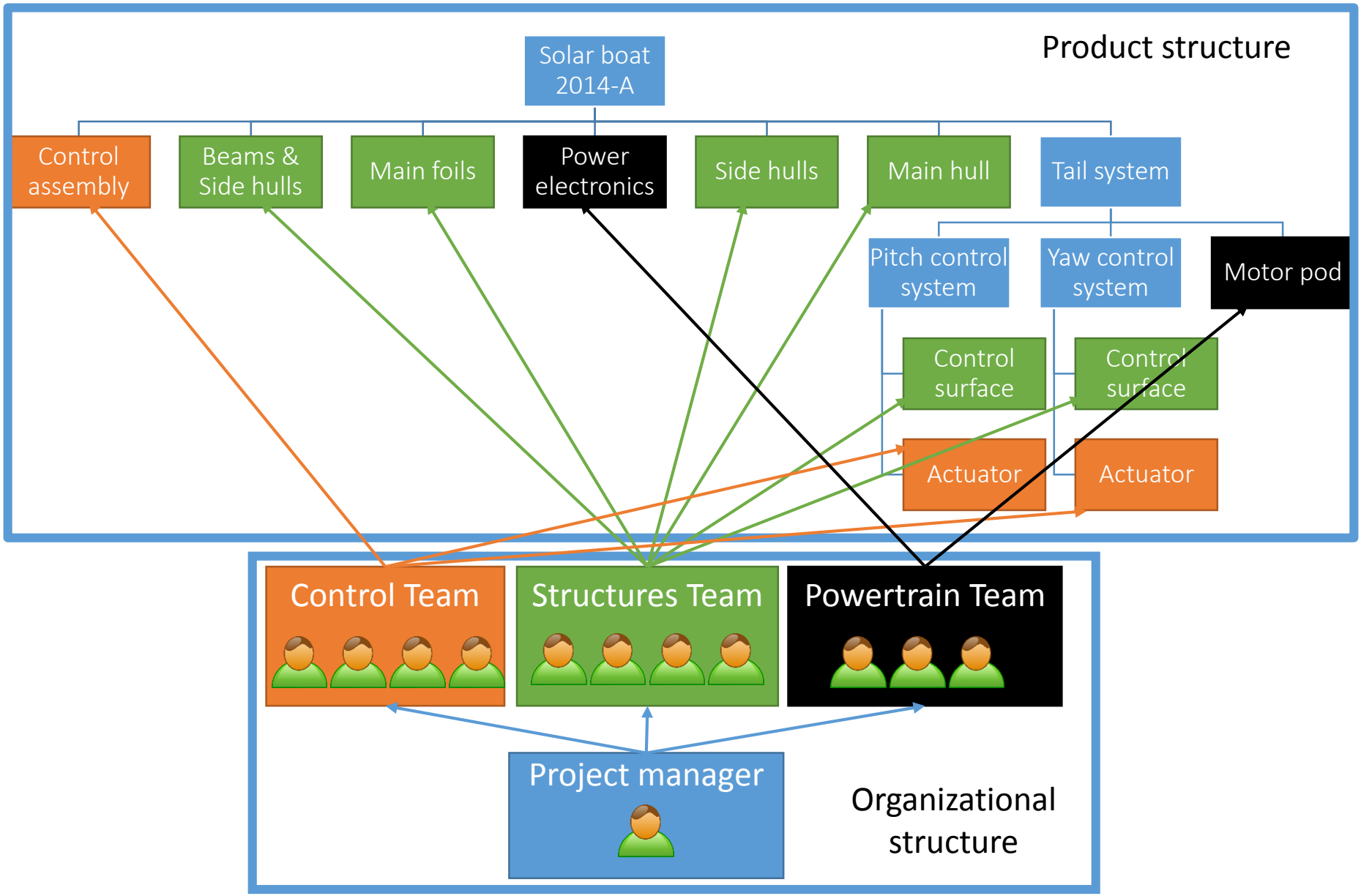
"2014-A" Ranked 3rd in Race

14kg
2.4m x 2m

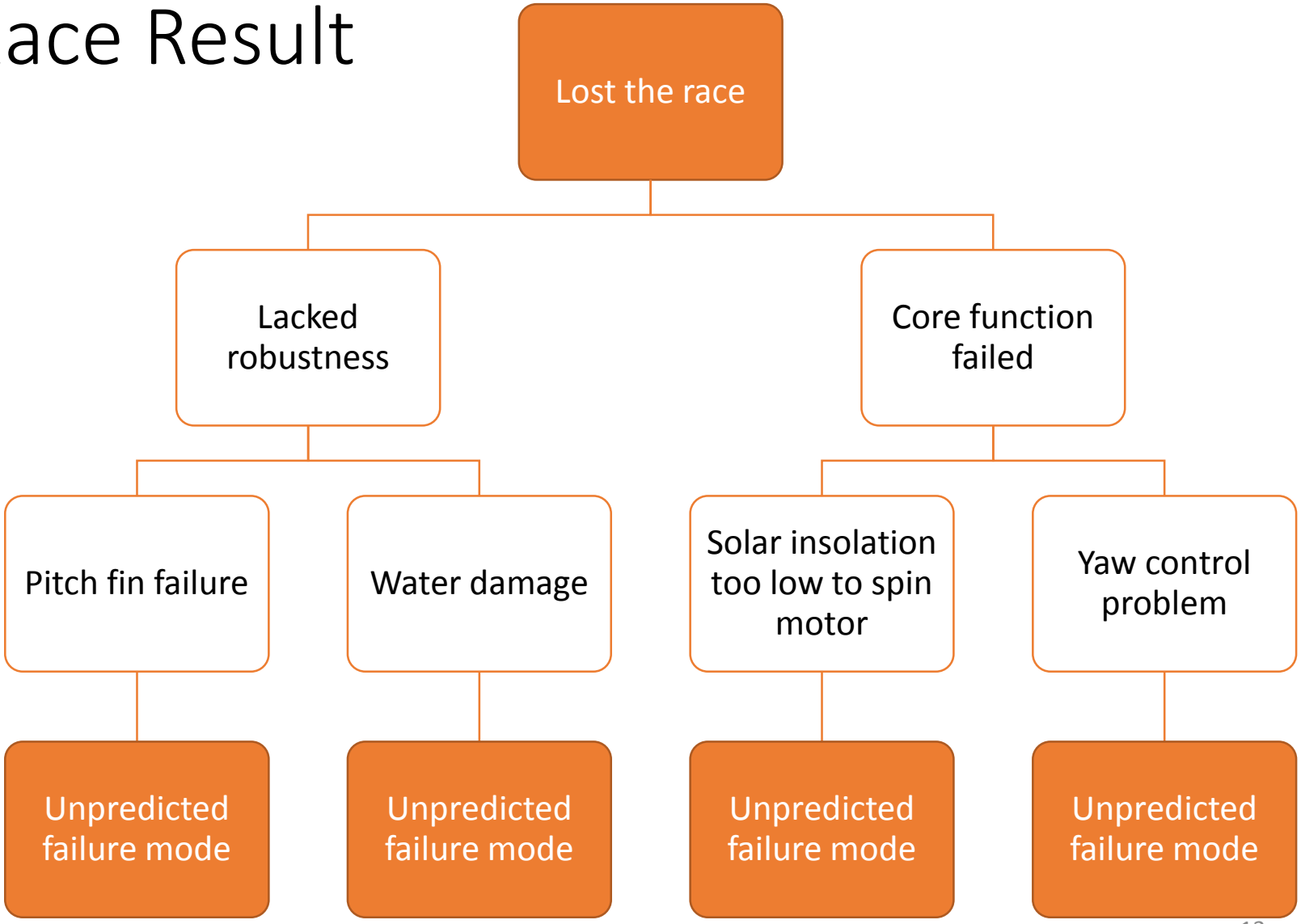




SolarBoat 2014: Project structure



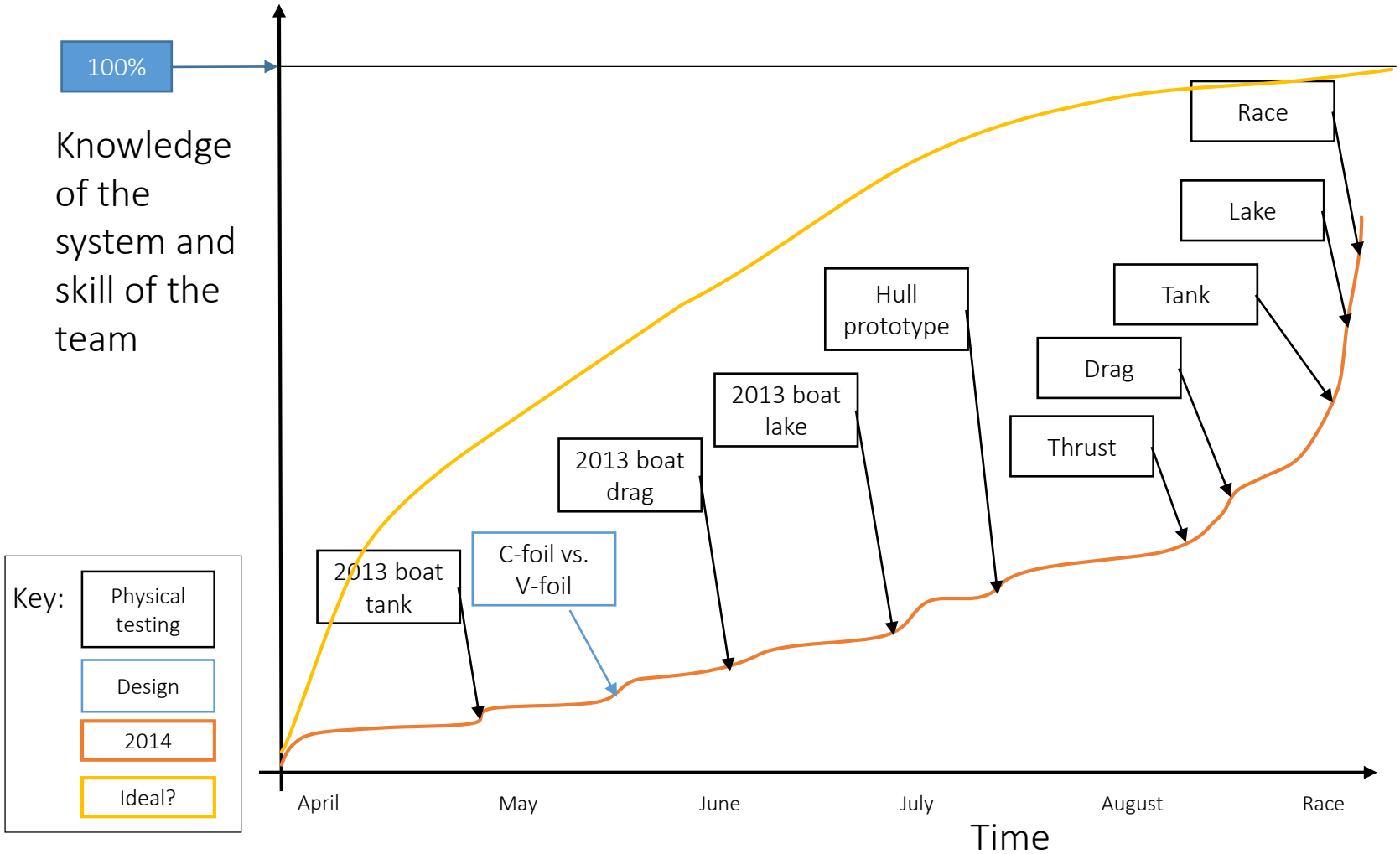
Reflection on SolarBoat 2014: Race Result



Research purpose and method

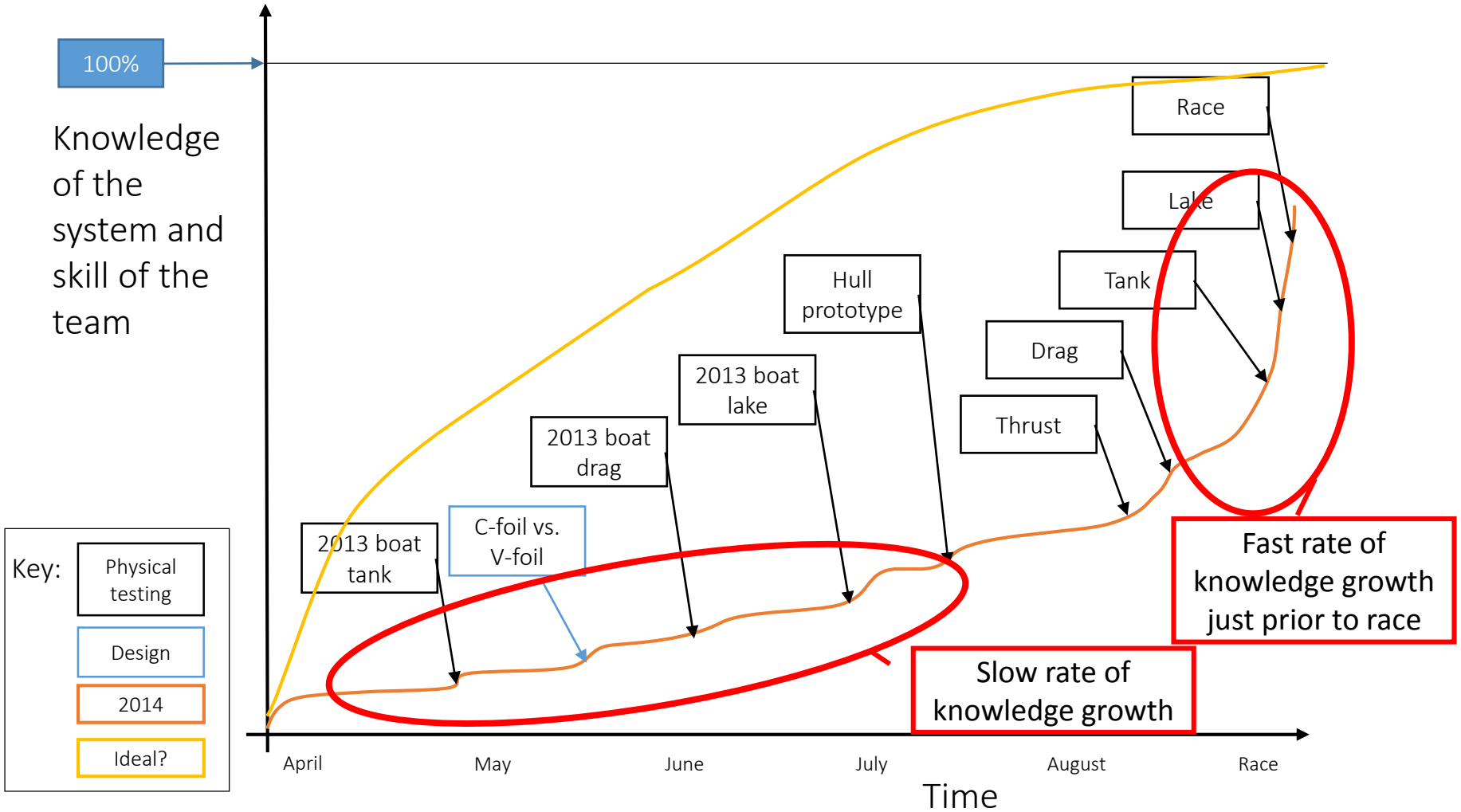
- Research purpose:
  - Propose a better way to develop such a boat
- Method:
  - Analyze and describe the project using V-Model views
- Output:
  - Propose changes for future development
  - Propose future research

Knowledge / Skill Growth curve: SolarBoat 2014



Adapted from model proposed in: Scheithauer 2012

Knowledge / Skill Growth curve: SolarBoat 2014

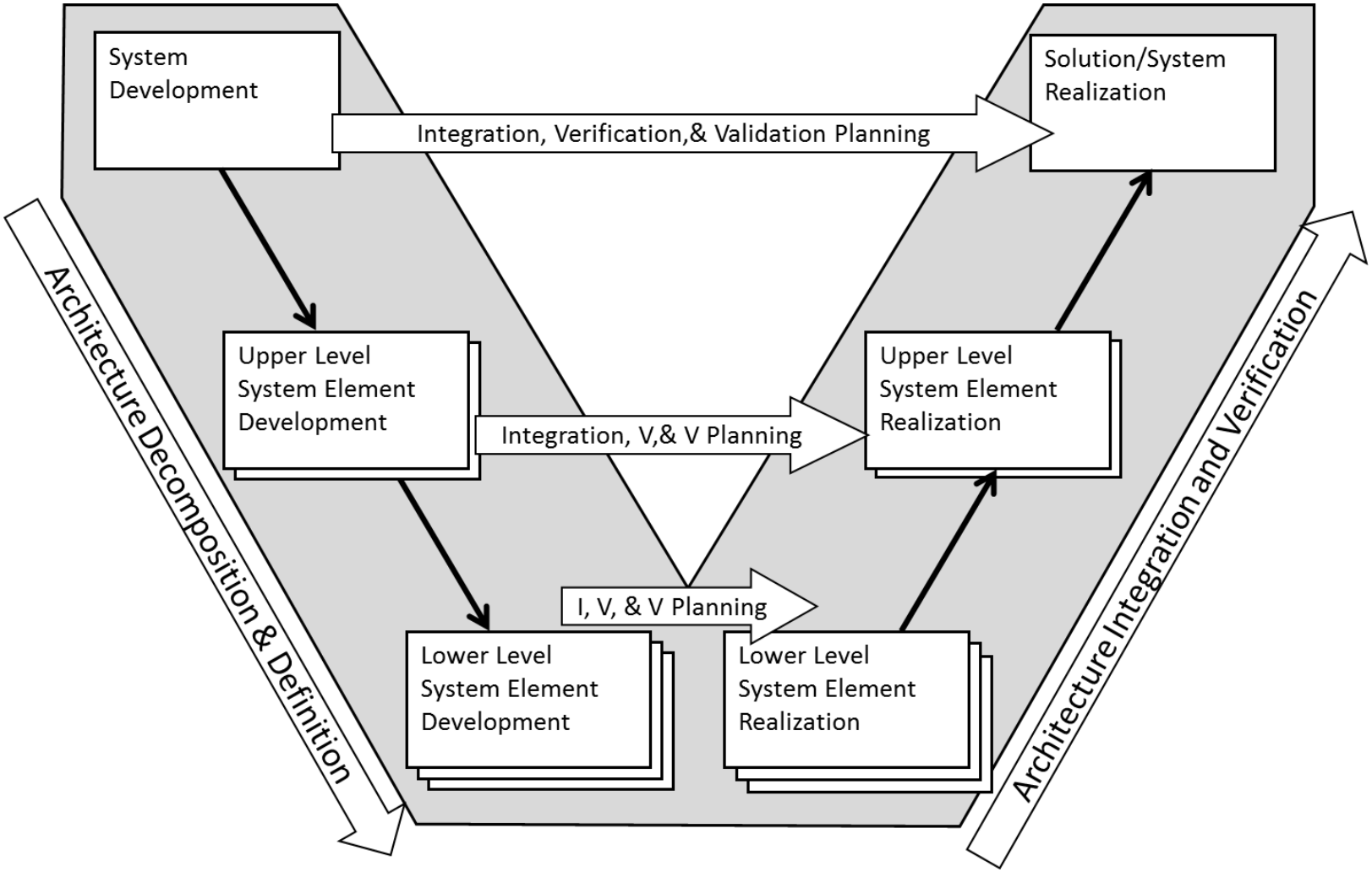


Adapted from model proposed in: Scheithauer 2012

Presentation Overview

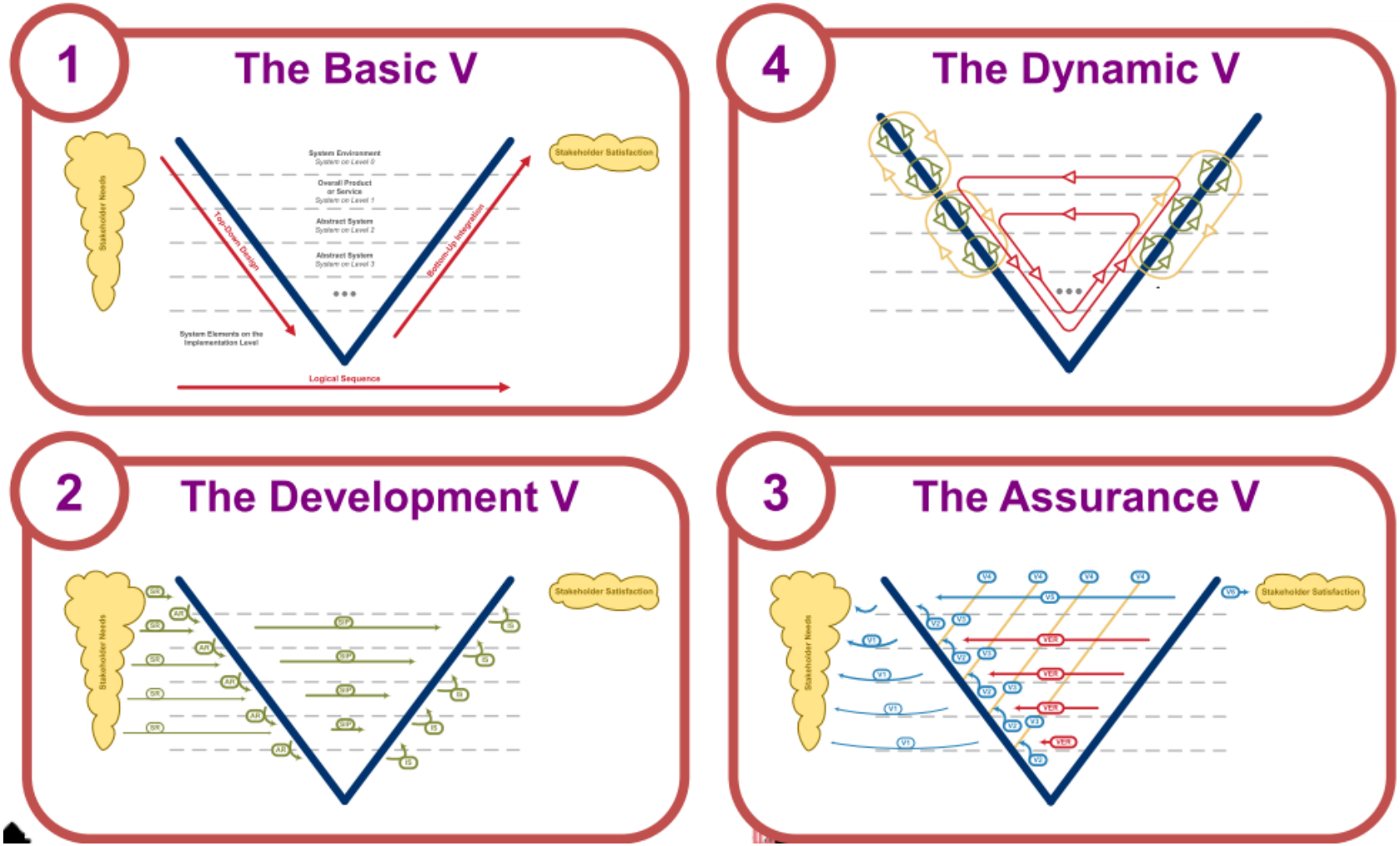
1. Definitions:
   1. SolarBoat
   2. Systems Engineering
2. SolarBoat 2014 results
3. **<u>V-Model to analyse development and determine alternative work</u>**
4. Grouping solutions and building a new development plan
5. Conclusions

The V-Model



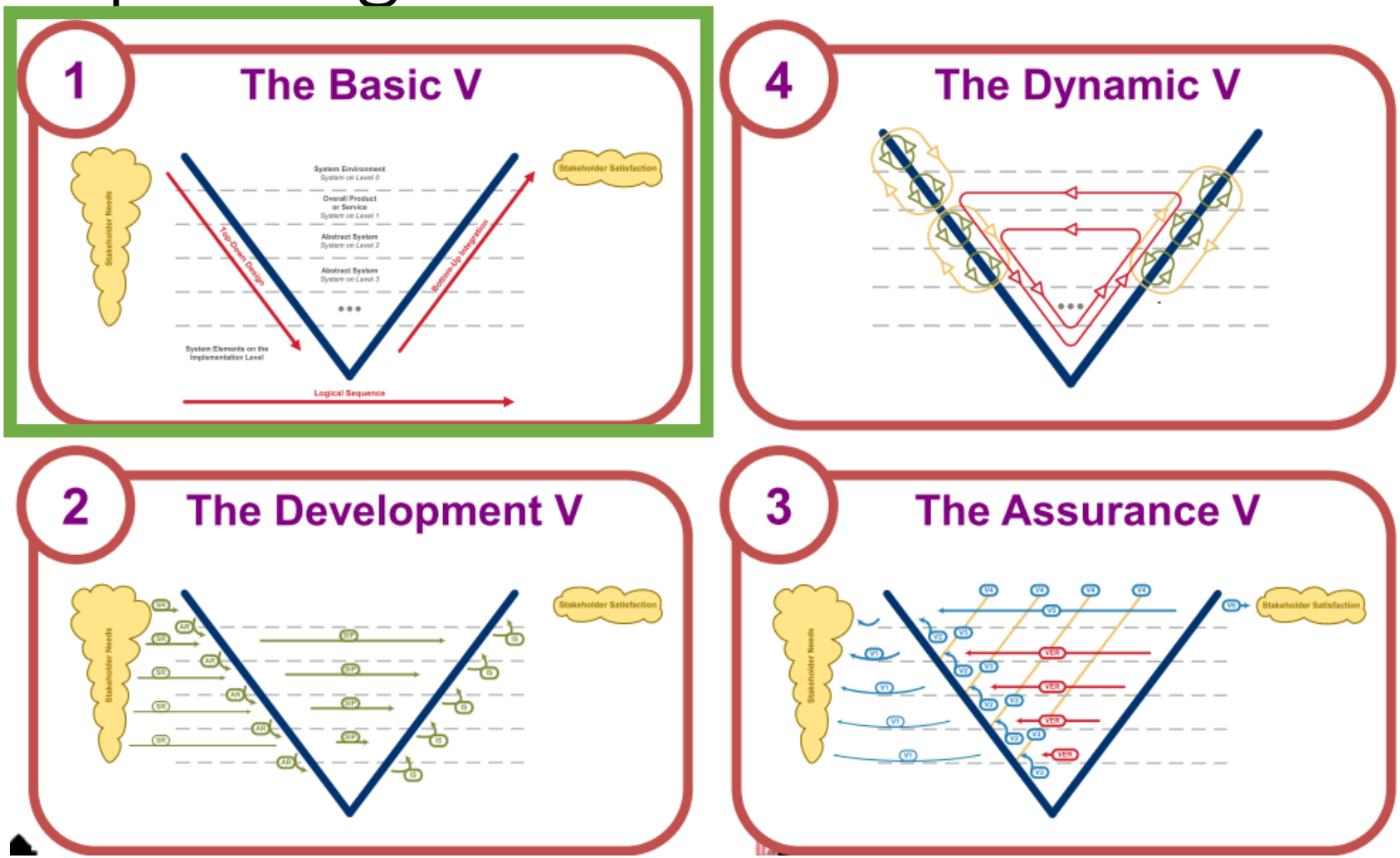
Adapted from: INCOSE 2011

Updating the V-Model



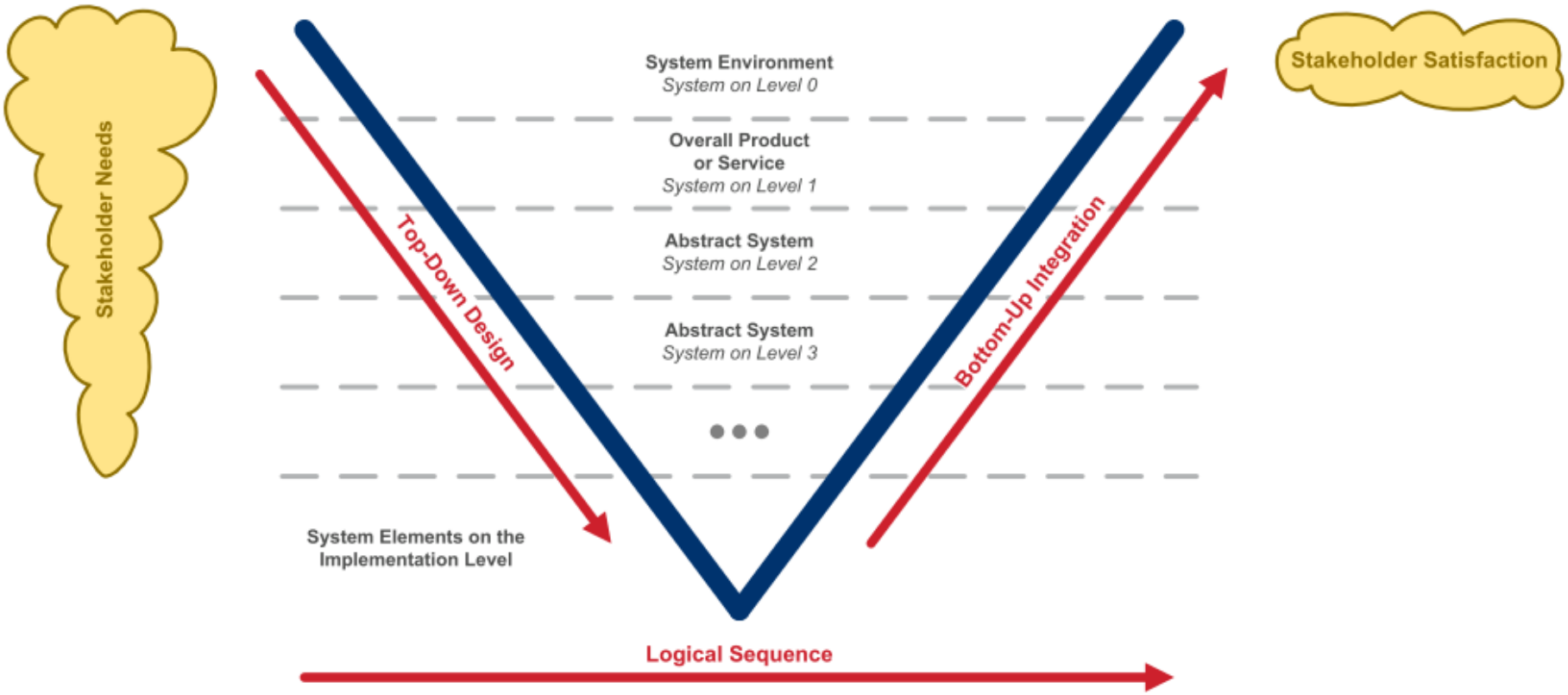
From: Scheithauer and Forsberg, 2013.

Updating the V-Model

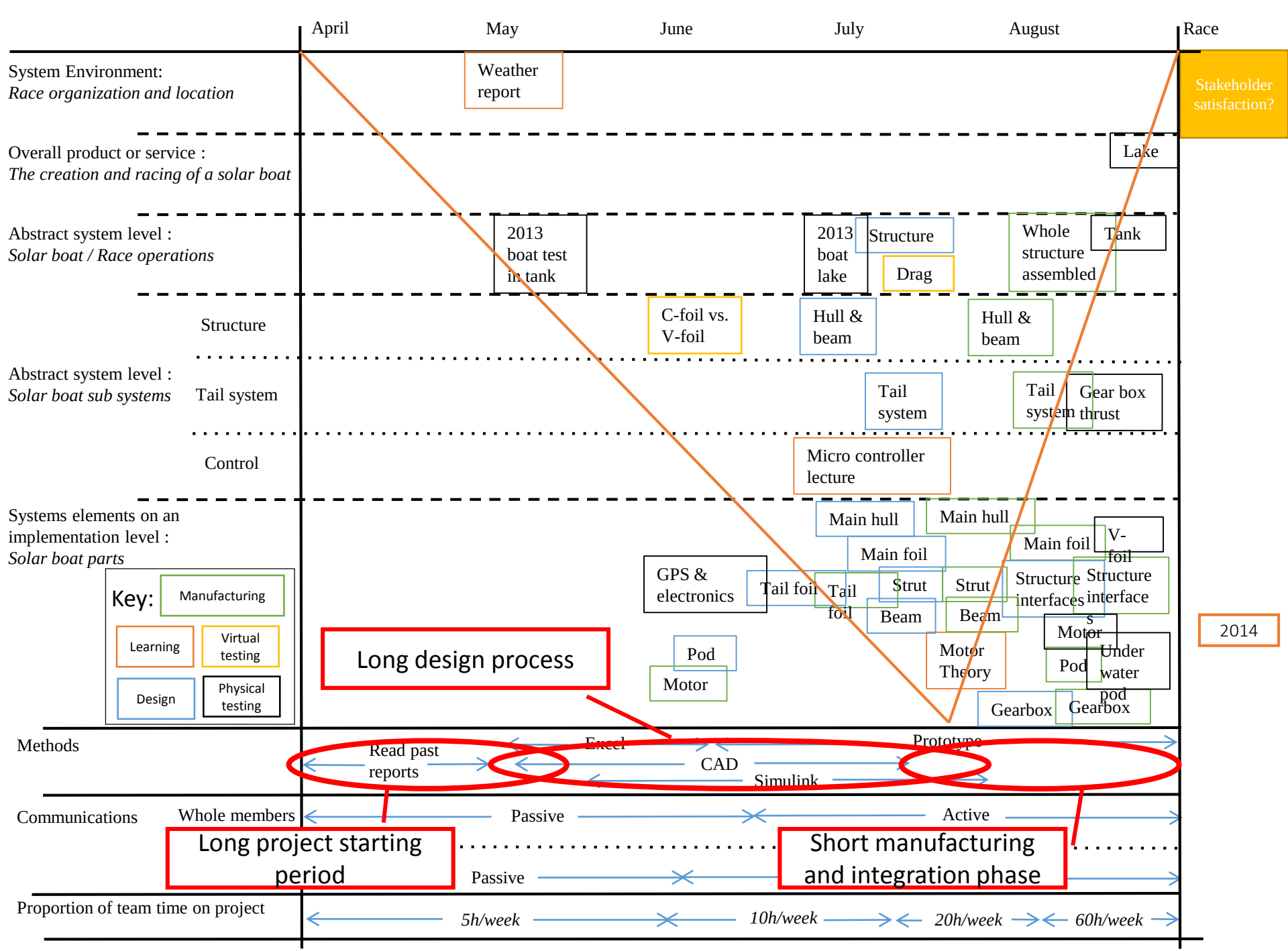


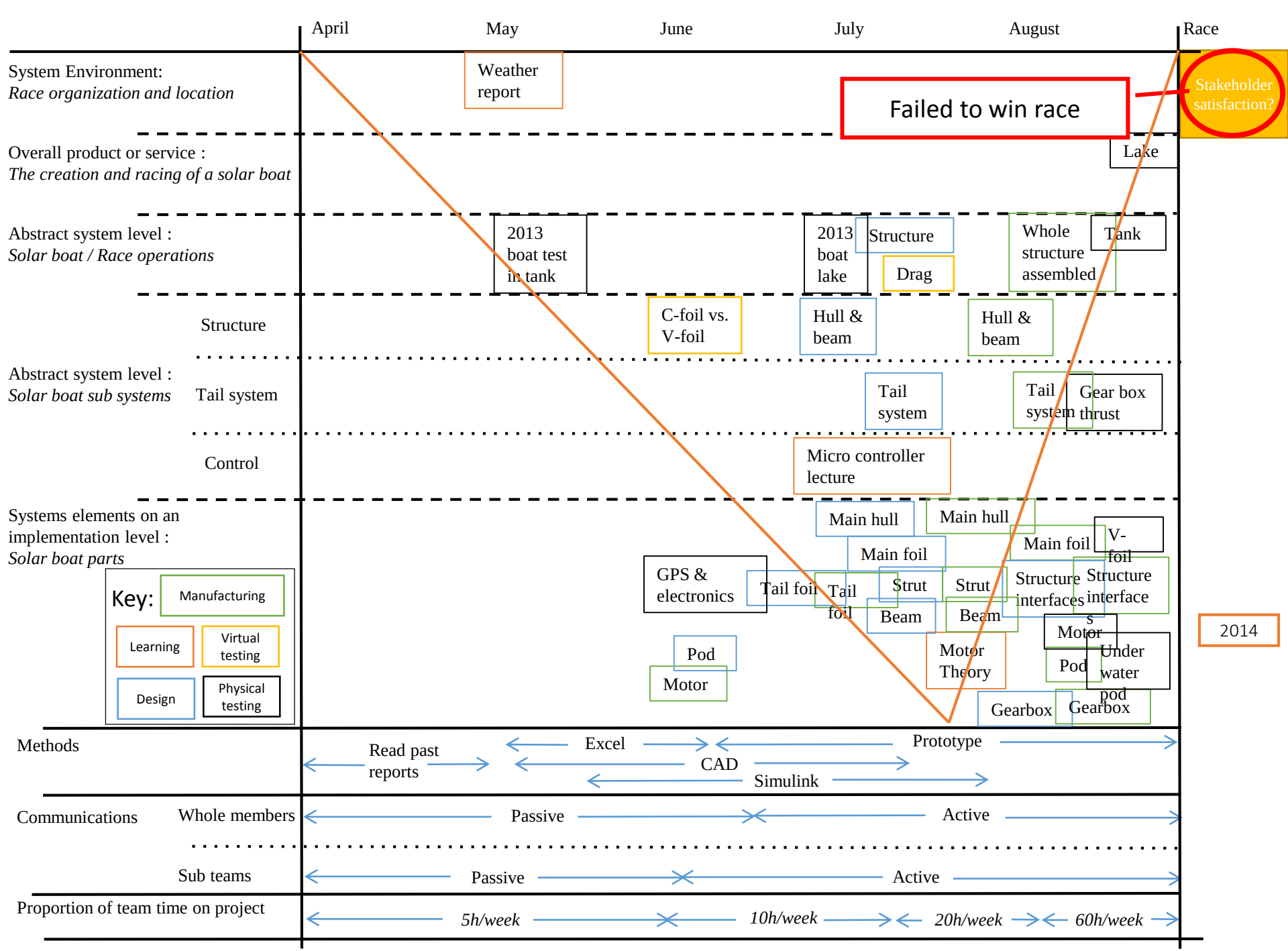
From: Scheithauer and Forsberg, 2013.

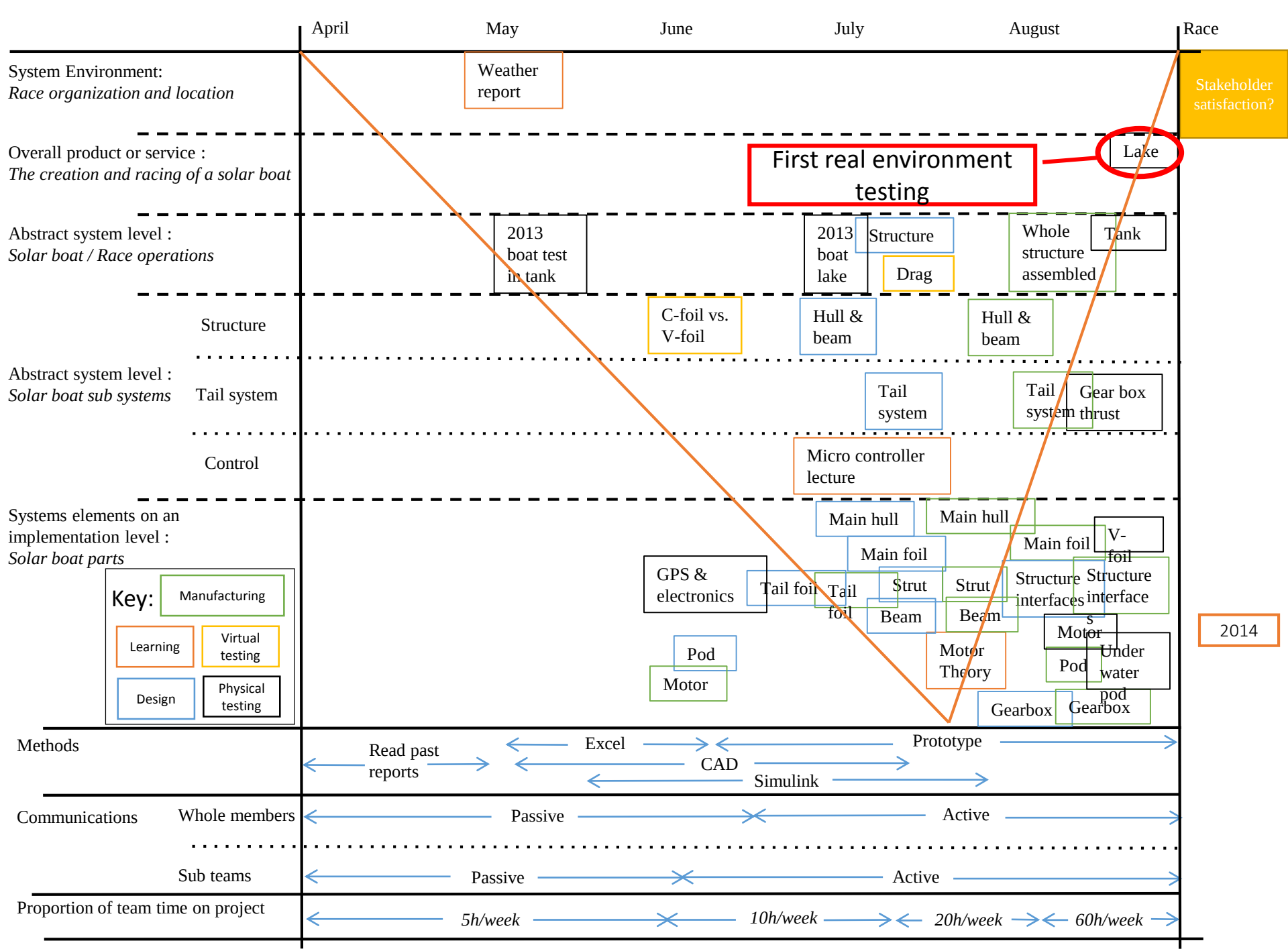
Basic V

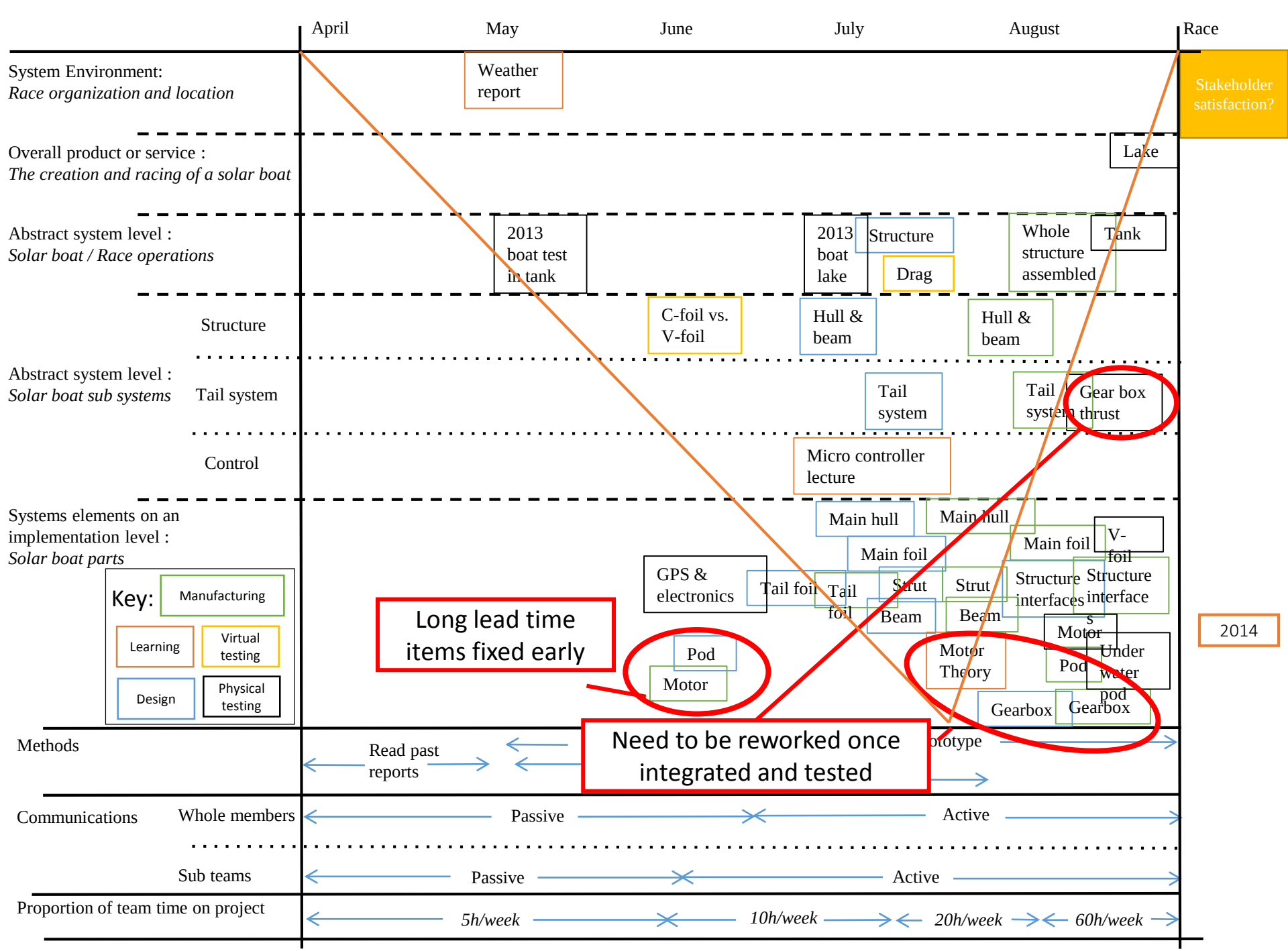


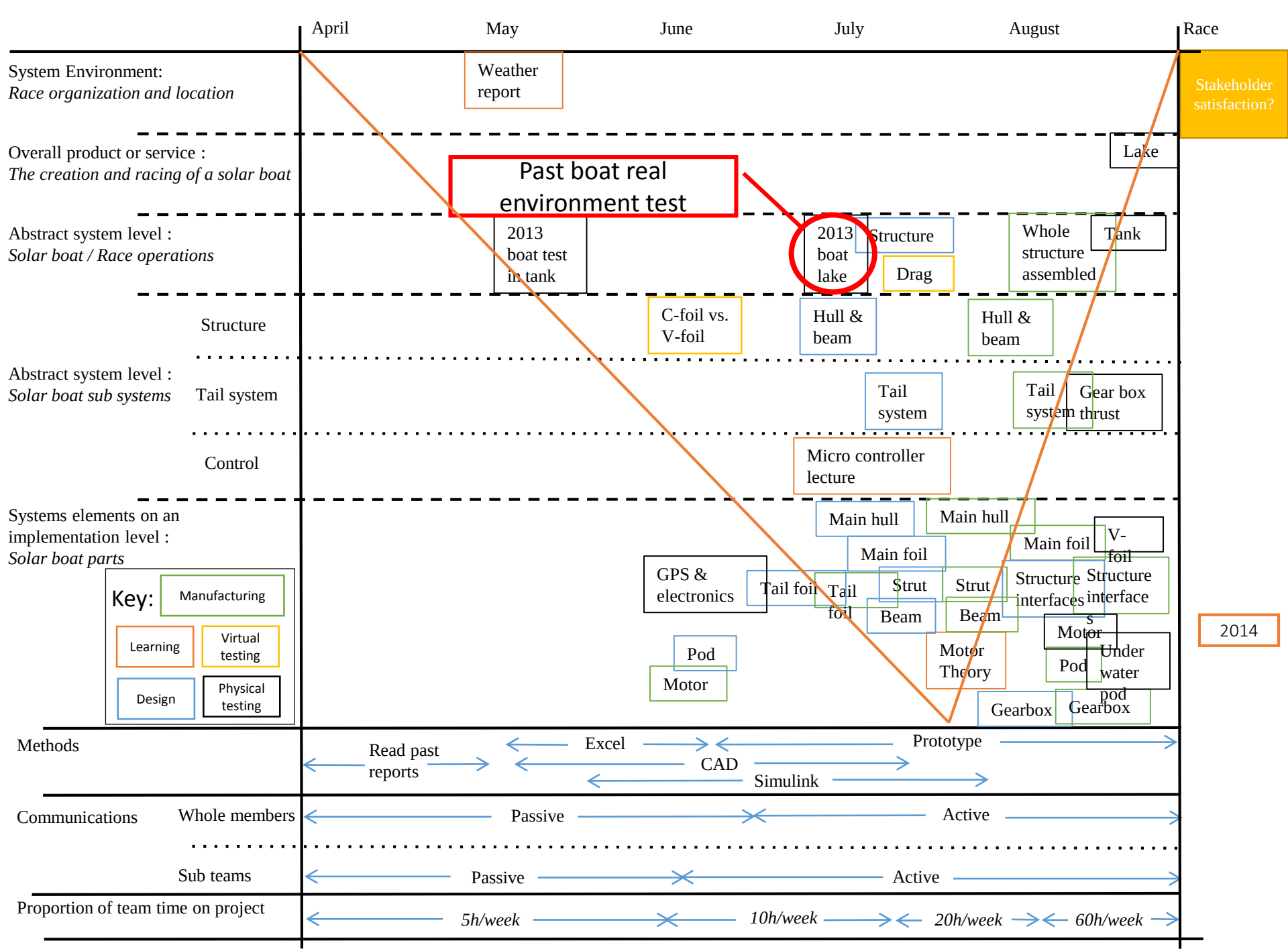
From: Scheithauer and Forsberg, 2013.


April
May
June
July
August
Race
System Environment:
Race organization and location
Weather report
Stakeholder satisfaction?
Overall product or service :
The creation and racing of a solar boat
Lake
Abstract system level :
Solar boat / Race operations
2013 boat test in tank
2013 boat lake
Structure
Drag
Whole structure assembled
Tank
Structure
C-foil vs. V-foil
Hull & beam
Hull & beam
Abstract system level :
Solar boat sub systems
Tail system
Tail system
Tail system
Gear box thrust
Control
Micro controller lecture
Systems elements on an implementation level :
Solar boat parts
Main hull
Main hull
Main foil
Main foil
V-foil
GPS & electronics
Tail foil
Tail foil
Strut
Strut
Structure interfaces
Structure interfaces
Beam
Beam
Motor
Pod
Motor
Motor Theory
Pod
Under water pod
Gearbox
Gearbox
Key:
Manufacturing
Learning
Virtual testing
Design
Physical testing
Long design process
2014
Methods
Read past reports
Excel
CAD
Simulink
Prototype
Communications
Whole members
Passive
Active
Passive
Long project starting period
Short manufacturing and integration phase
Proportion of team time on project
5h/week
10h/week
20h/week
60h/week

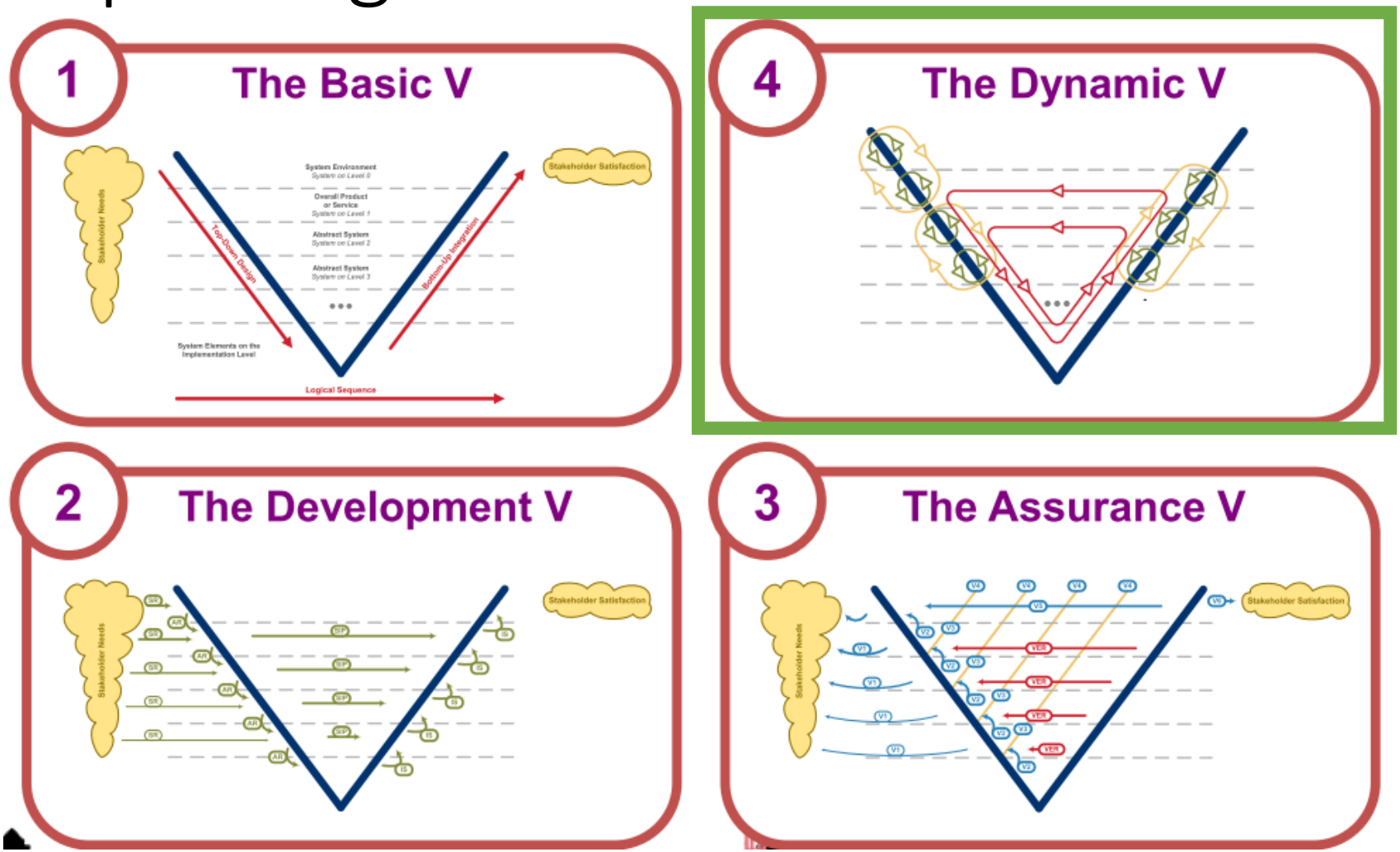

April
May
June
July
August
Race
System Environment:
Race organization and location
Weather report
Failed to win race
Stakeholder satisfaction?
Overall product or service :
The creation and racing of a solar boat
Lake
Abstract system level :
Solar boat / Race operations
2013 boat test in tank
2013 boat lake
Structure
Drag
Whole structure assembled
Tank
Structure
C-foil vs. V-foil
Hull & beam
Hull & beam
Abstract system level :
Solar boat sub systems
Tail system
Tail system
Tail system
Gear box thrust
Control
Micro controller lecture
Systems elements on an implementation level :
Solar boat parts
Main hull
Main hull
Main foil
Main foil
V-foil
GPS & electronics
Tail foil
Tail foil
Strut
Strut
Structure interfaces
Structure interfaces
Beam
Beam
Motor
Pod
Motor
Motor Theory
Pod
Under water pod
Gearbox
Gearbox
Key:
Manufacturing
Learning
Virtual testing
Design
Physical testing
2014
Methods
Read past reports
Excel
CAD
Simulink
Prototype
Communications
Whole members
Passive
Active
Sub teams
Passive
Active
Proportion of team time on project
5h/week
10h/week
20h/week
60h/week


April
May
June
July
August
Race
System Environment:
Race organization and location
Weather report
Stakeholder satisfaction?
Overall product or service :
The creation and racing of a solar boat
First real environment testing
Lake
Abstract system level :
Solar boat / Race operations
2013 boat test in tank
2013 boat lake
Structure
Drag
Whole structure assembled
Tank
Structure
C-foil vs. V-foil
Hull & beam
Hull & beam
Abstract system level :
Solar boat sub systems
Tail system
Tail system
Tail system
Gear box thrust
Control
Micro controller lecture
Systems elements on an implementation level :
Solar boat parts
Main hull
Main hull
Main foil
Main foil
V-foil
GPS & electronics
Tail foil
Tail foil
Strut
Strut
Structure interfaces
Structure interfaces
Beam
Beam
Motor
Pod
Motor
Motor Theory
Pod
Under water pod
Gearbox
Gearbox
Key:
Manufacturing
Learning
Virtual testing
Design
Physical testing
2014
Methods
Read past reports
Excel
CAD
Simulink
Prototype
Communications
Whole members
Passive
Active
Sub teams
Passive
Active
Proportion of team time on project
5h/week
10h/week
20h/week
60h/week


April
May
June
July
August
Race
System Environment:
Race organization and location
Weather report
Stakeholder satisfaction?
Overall product or service :
The creation and racing of a solar boat
Lake
Abstract system level :
Solar boat / Race operations
2013 boat test in tank
2013 boat lake
Structure
Drag
Whole structure assembled
Tank
Structure
C-foil vs. V-foil
Hull & beam
Hull & beam
Abstract system level :
Solar boat sub systems
Tail system
Tail system
Tail system
Gear box thrust
Control
Micro controller lecture
Systems elements on an implementation level :
Solar boat parts
Main hull
Main hull
Main foil
Main foil
V-foil
GPS & electronics
Tail foil
Tail foil
Strut
Strut
Structure interfaces
Structure interfaces
Beam
Beam
Motor
Pod
Motor
Motor Theory
Pod
Under water pod
Gearbox
Gearbox
Key:
Manufacturing
Learning
Virtual testing
Design
Physical testing
Long lead time items fixed early
Need to be reworked once integrated and tested
2014
Methods
Read past reports
ototype
Communications
Whole members
Passive
Active
Sub teams
Passive
Active
Proportion of team time on project
5h/week
10h/week
20h/week
60h/week

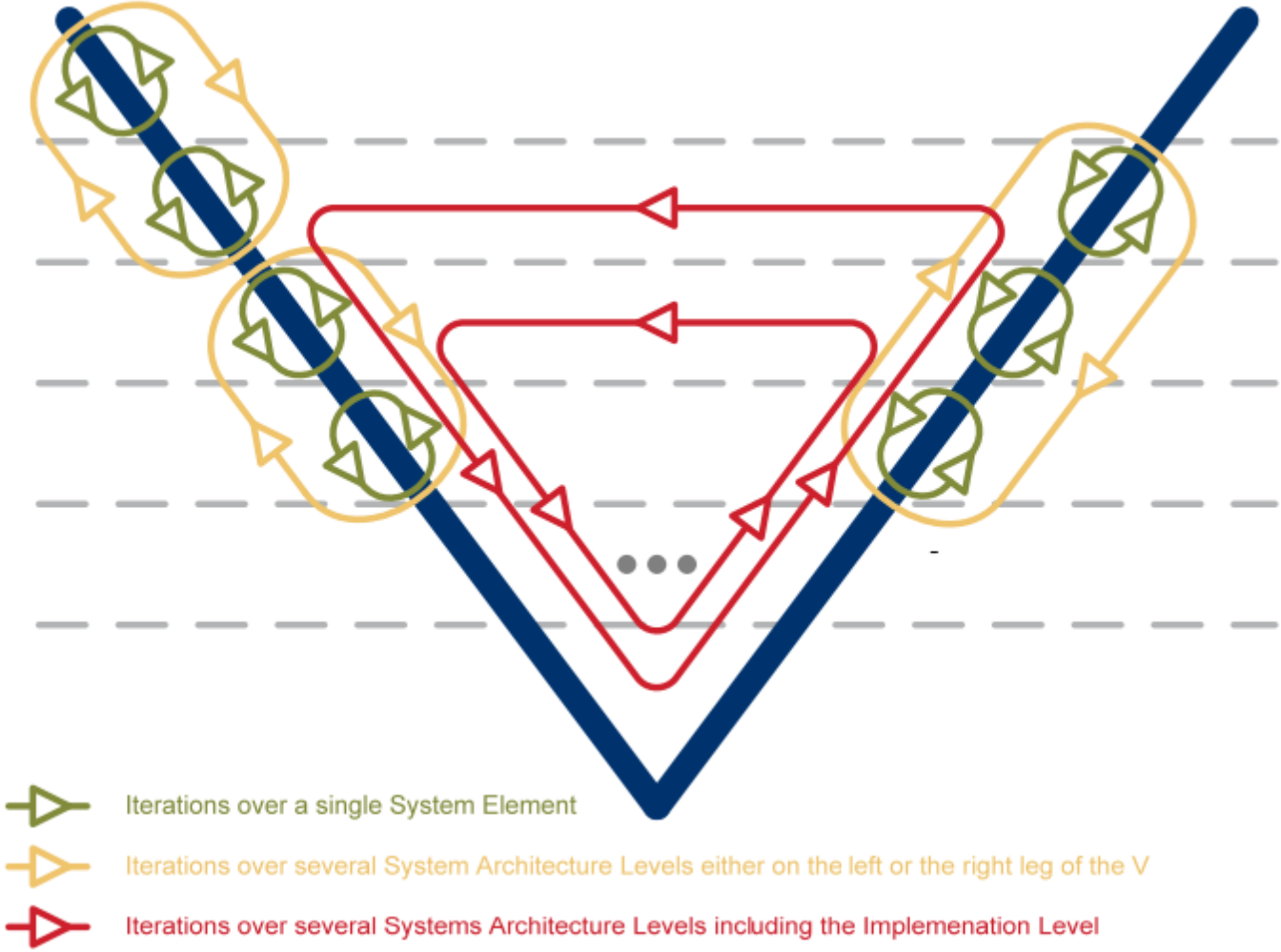

April
May
June
July
August
Race
System Environment:
Race organization and location
Weather report
Stakeholder satisfaction?
Overall product or service :
The creation and racing of a solar boat
Lake
Past boat real environment test
Abstract system level :
Solar boat / Race operations
2013 boat test in tank
2013 boat lake
Structure
Drag
Whole structure assembled
Tank
Structure
C-foil vs. V-foil
Hull & beam
Hull & beam
Abstract system level :
Solar boat sub systems
Tail system
Tail system
Tail system
Gear box thrust
Control
Micro controller lecture
Systems elements on an implementation level :
Solar boat parts
Main hull
Main hull
Main foil
Main foil
V-foil
GPS & electronics
Tail foil
Tail foil
Strut
Strut
Structure interfaces
Structure interfaces
Beam
Beam
Motor
Pod
Motor
Motor Theory
Pod
Under water pod
Gearbox
Gearbox
Key:
Manufacturing
Learning
Virtual testing
Design
Physical testing
2014
Methods
Read past reports
Excel
CAD
Simulink
Prototype
Communications
Whole members
Passive
Active
Sub teams
Passive
Active
Proportion of team time on project
5h/week
10h/week
20h/week
60h/week

Updating the V-Model



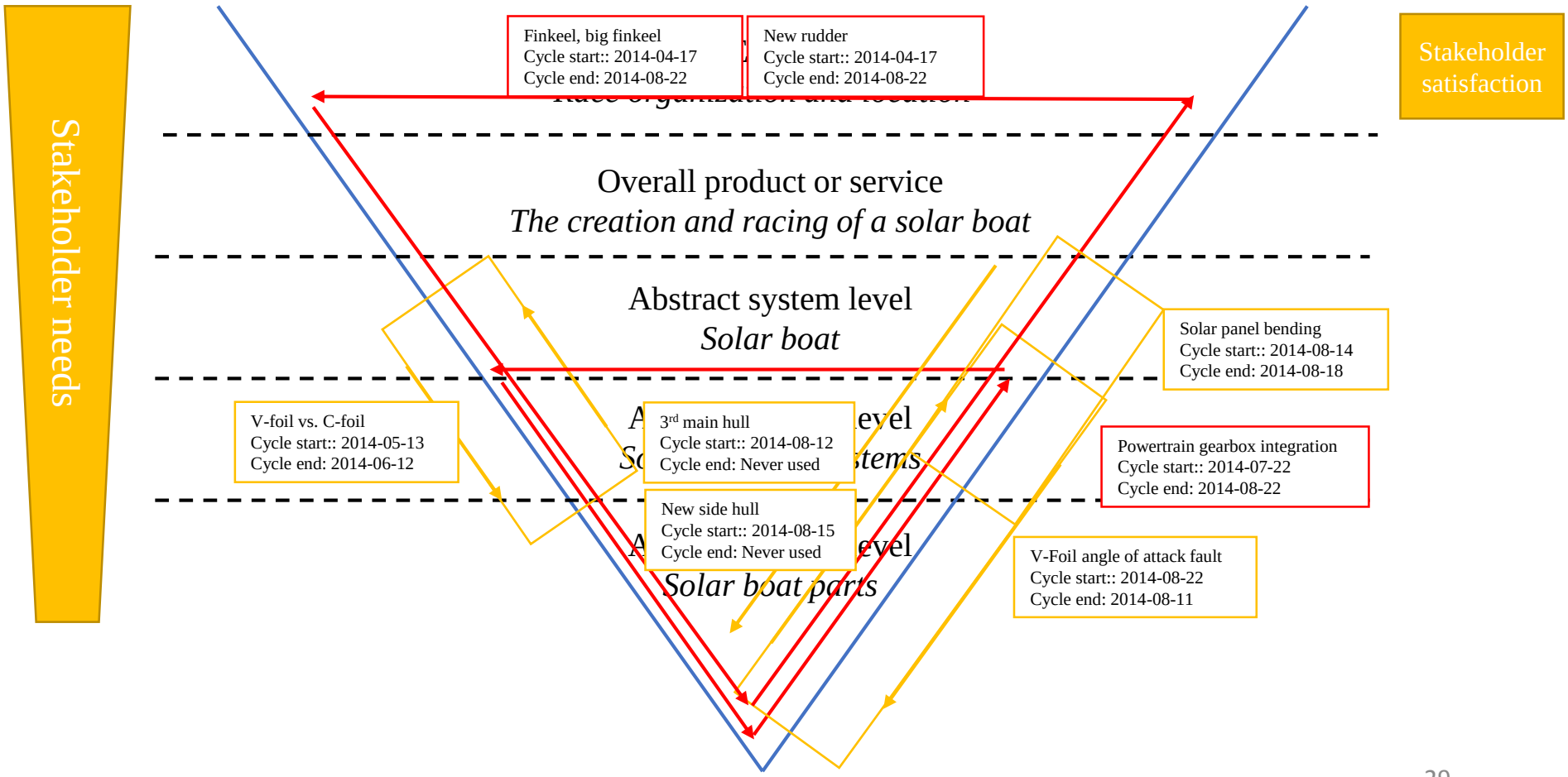
From: Scheithauer and Forsberg, 2013.

Dynamic V

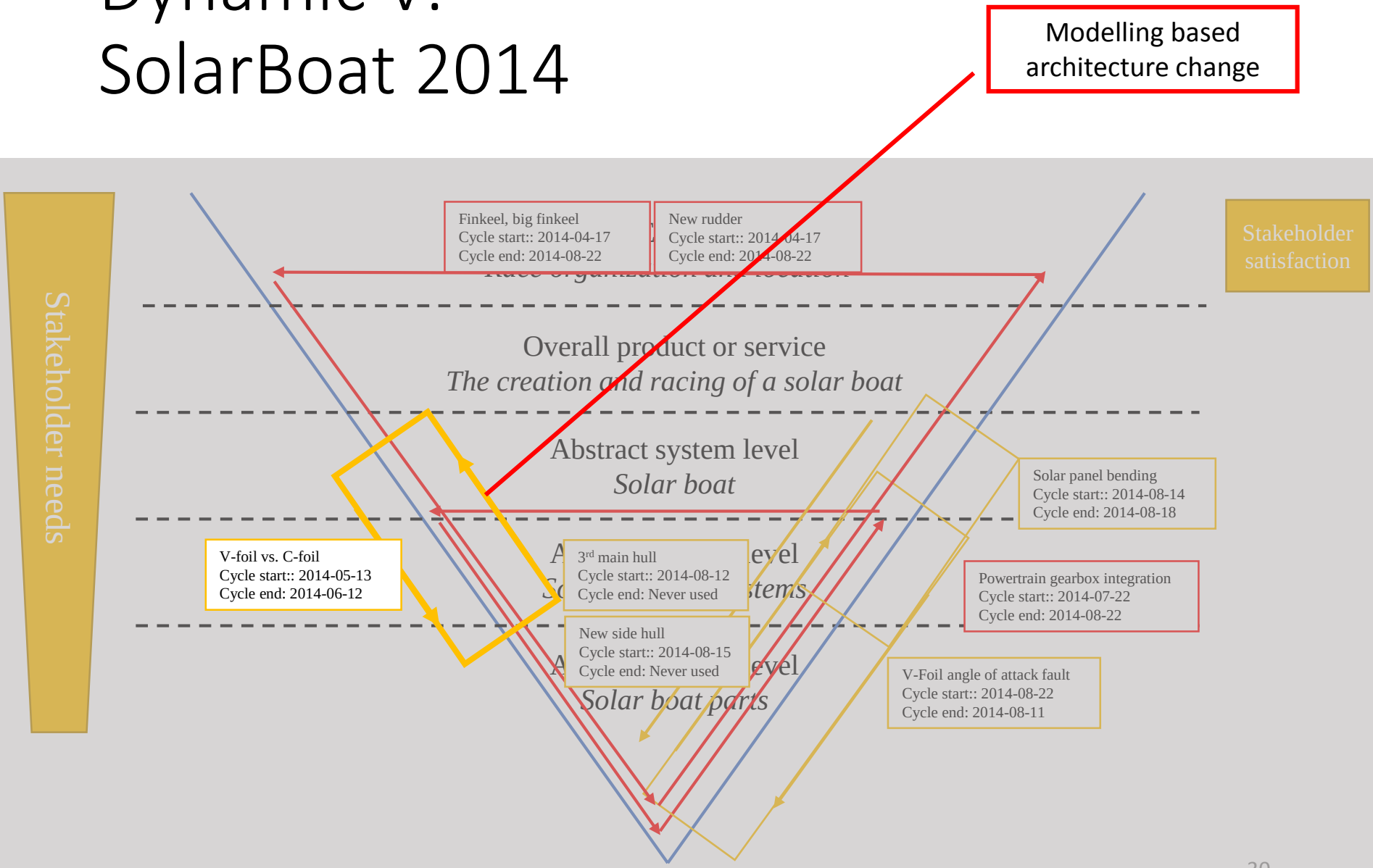


From: Scheithauer and Forsberg, 2013.

Dynamic V: SolarBoat 2014

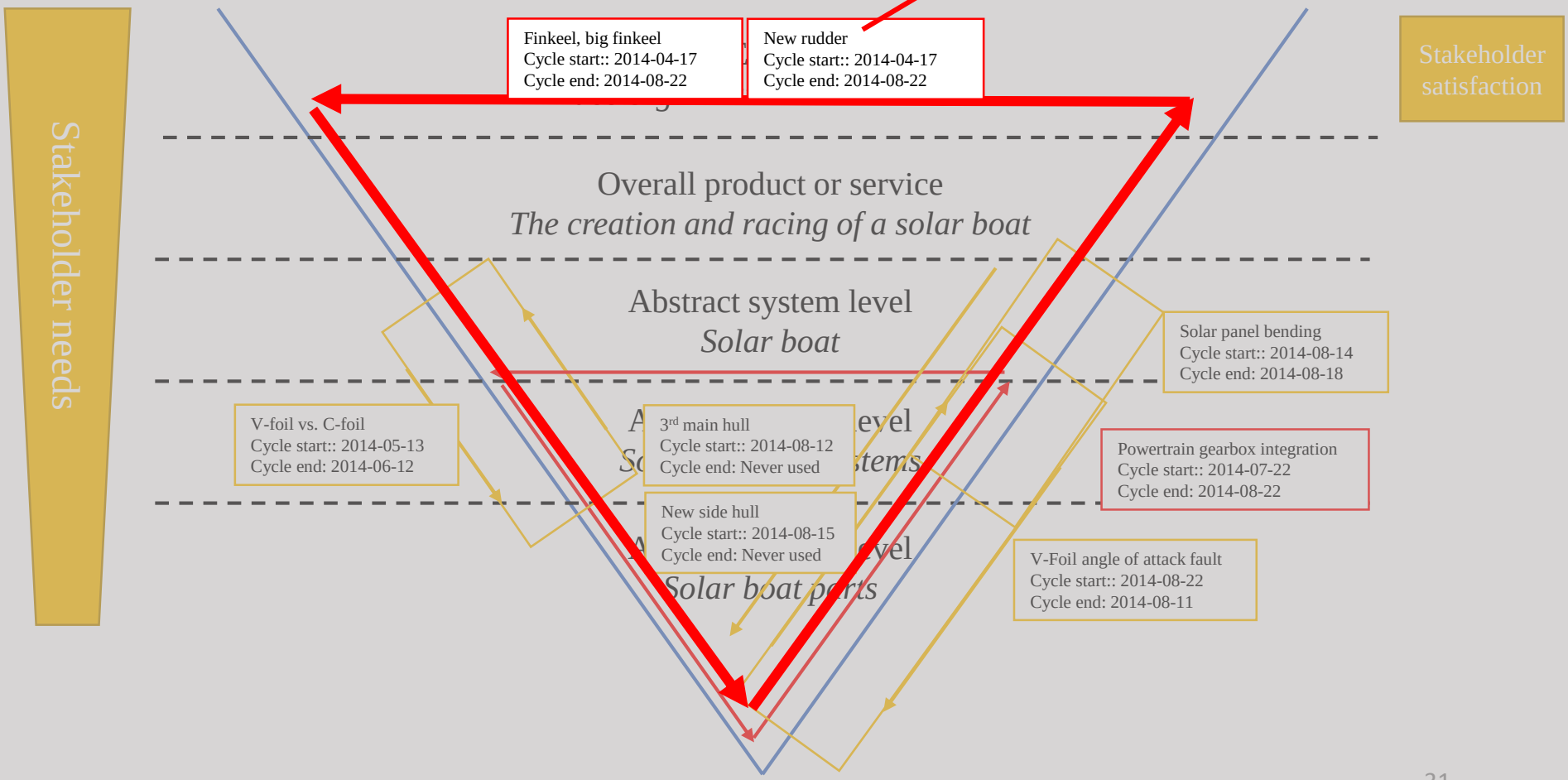


Dynamic V: SolarBoat 2014



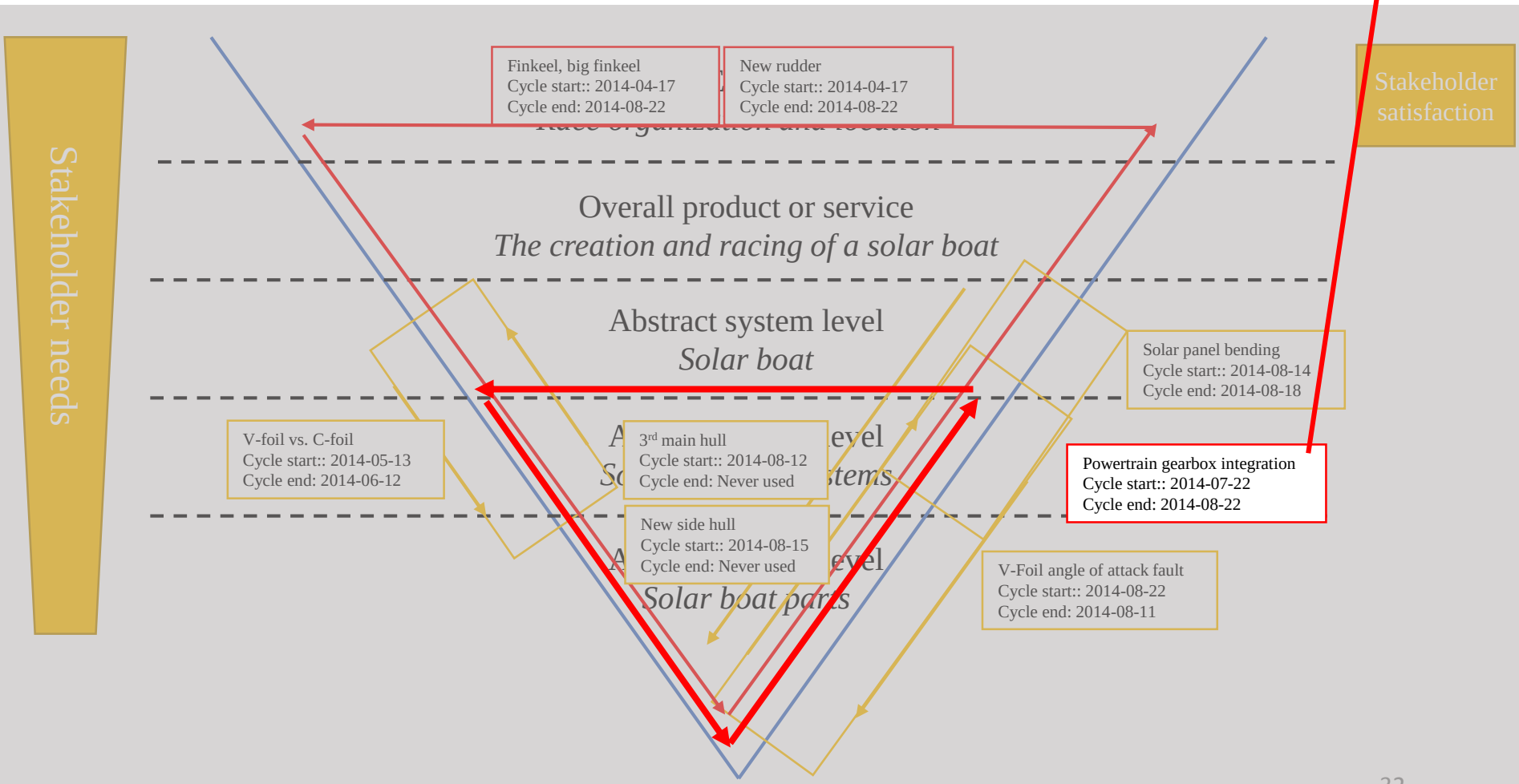
Dynamic V: SolarBoat 2014

Yaw control fault discovered day before race. Current architecture cannot solve this.

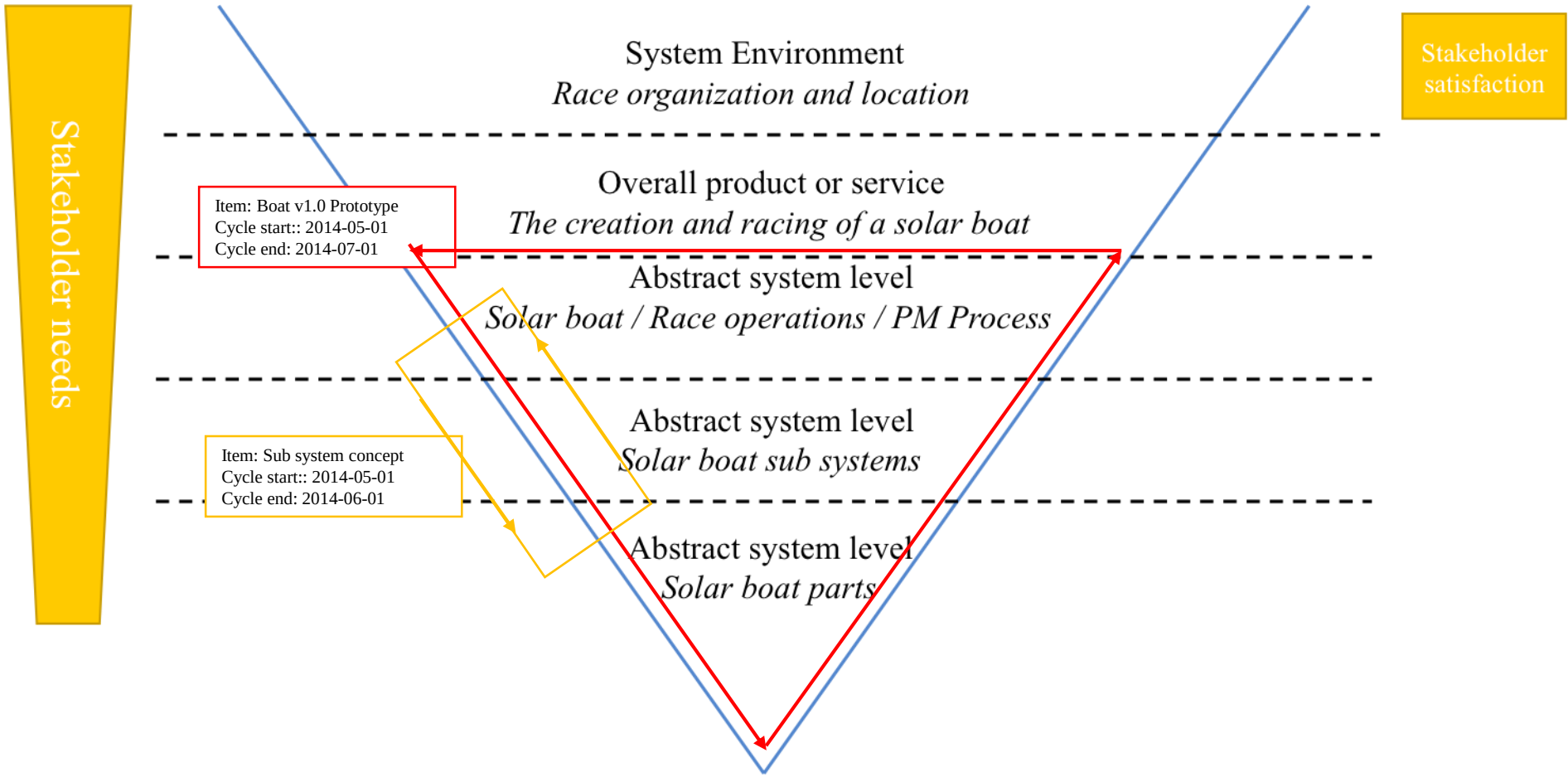


Dynamic V: SolarBoat 2014

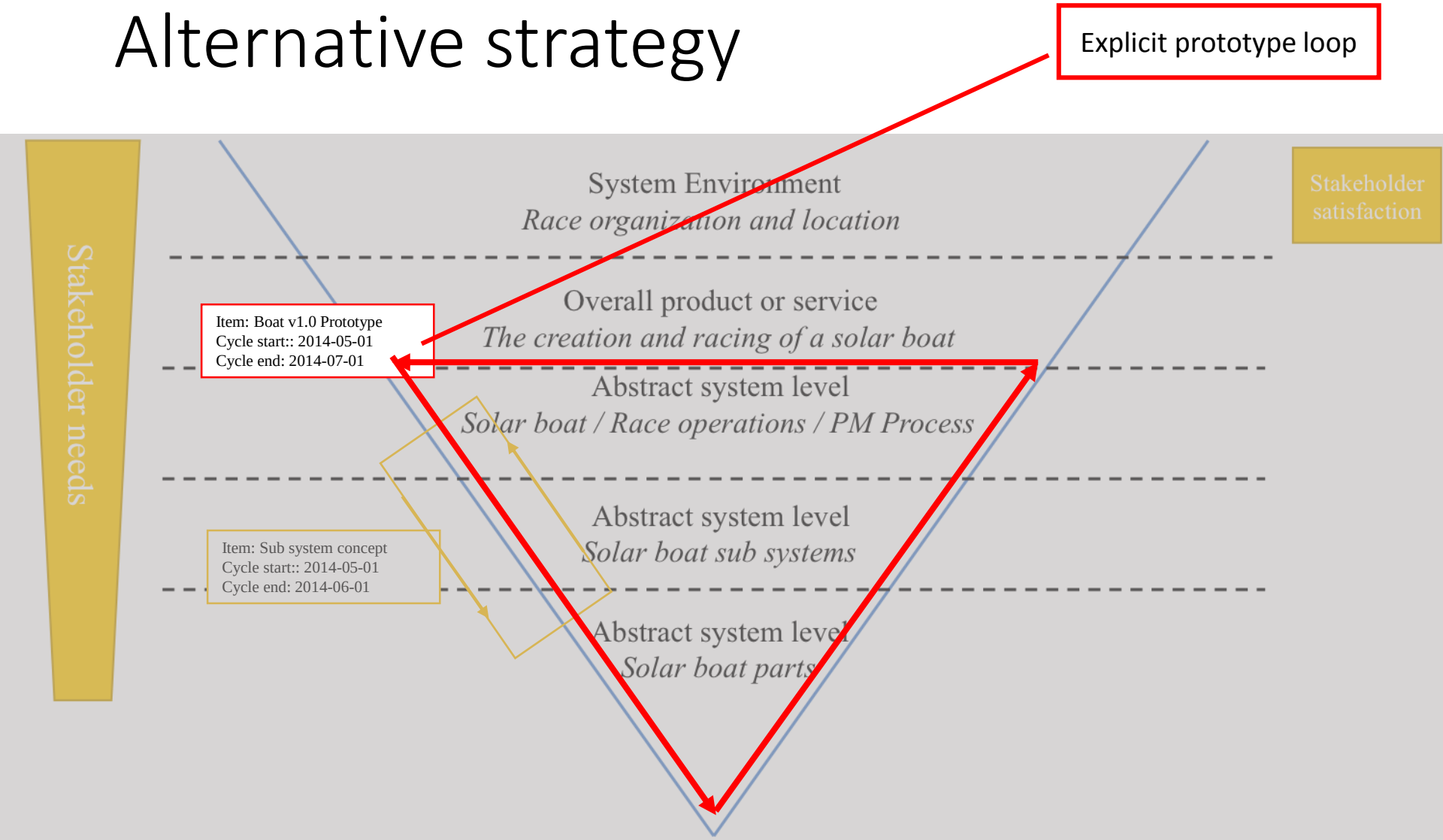
Gearbox rapidly integrated into the system 3 days before race



Dynamic V: Alternative strategy

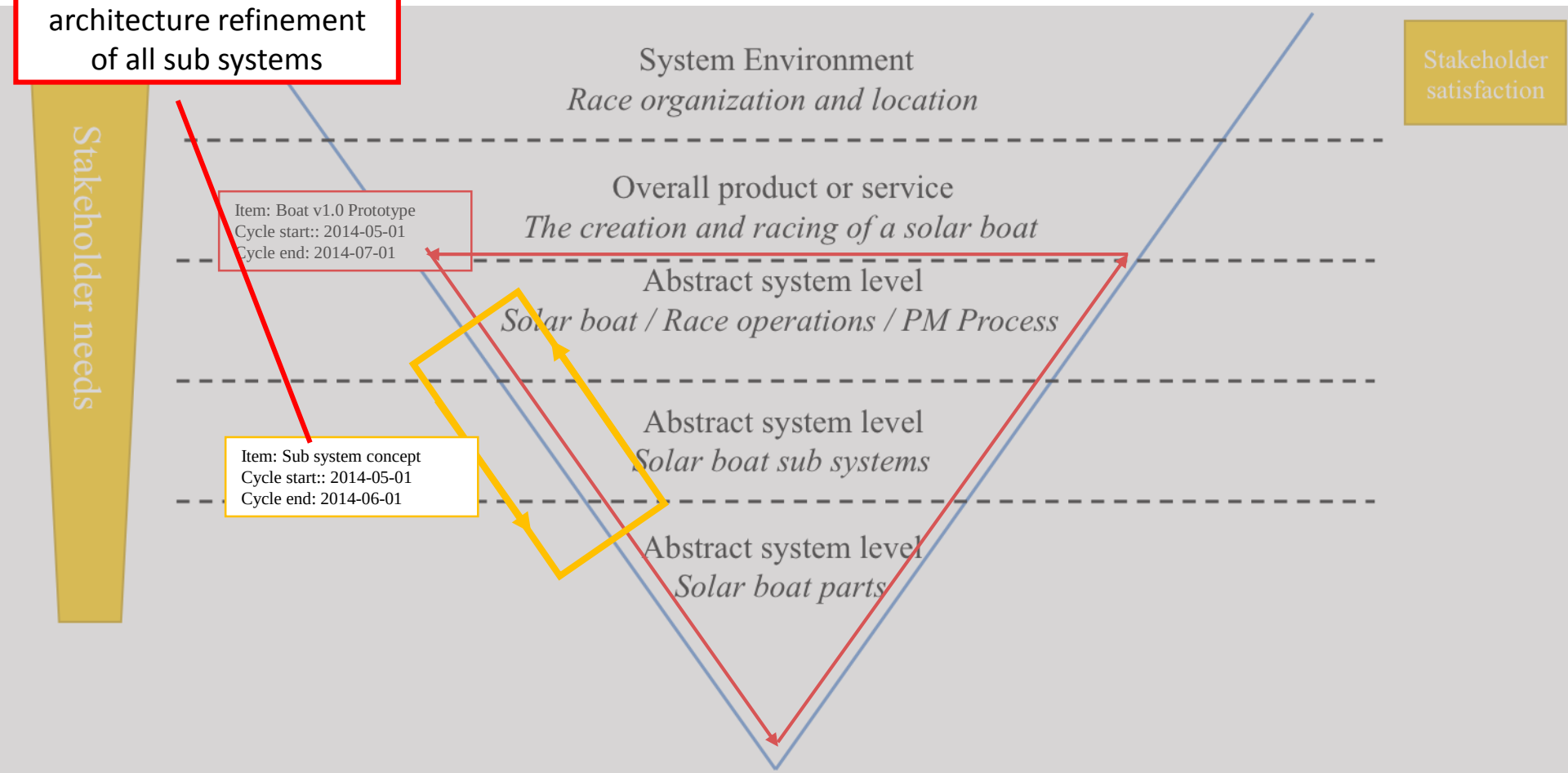


Dynamic V: Alternative strategy

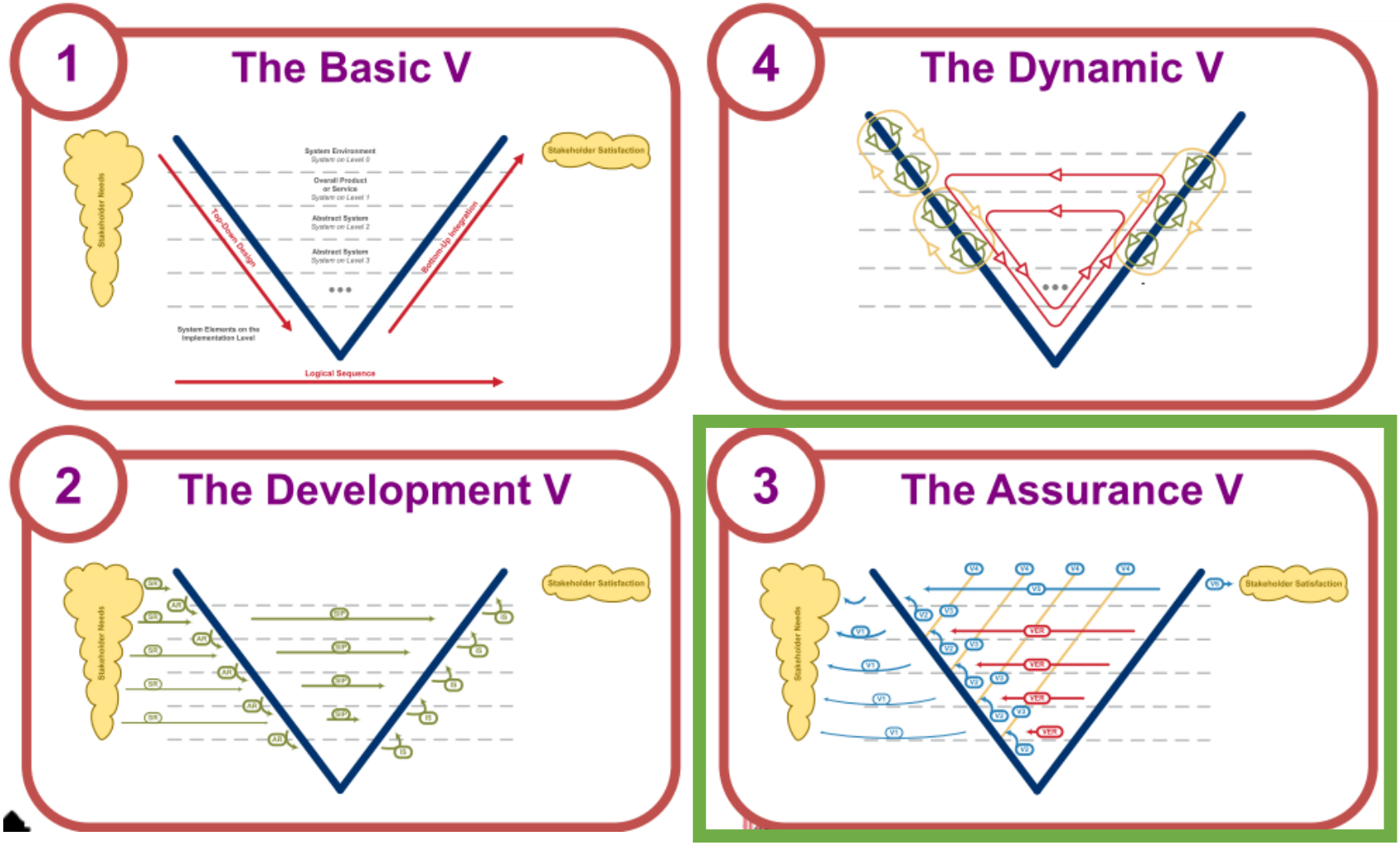


Dynamic V: Alternative strategy

Modelling based architecture refinement of all sub systems

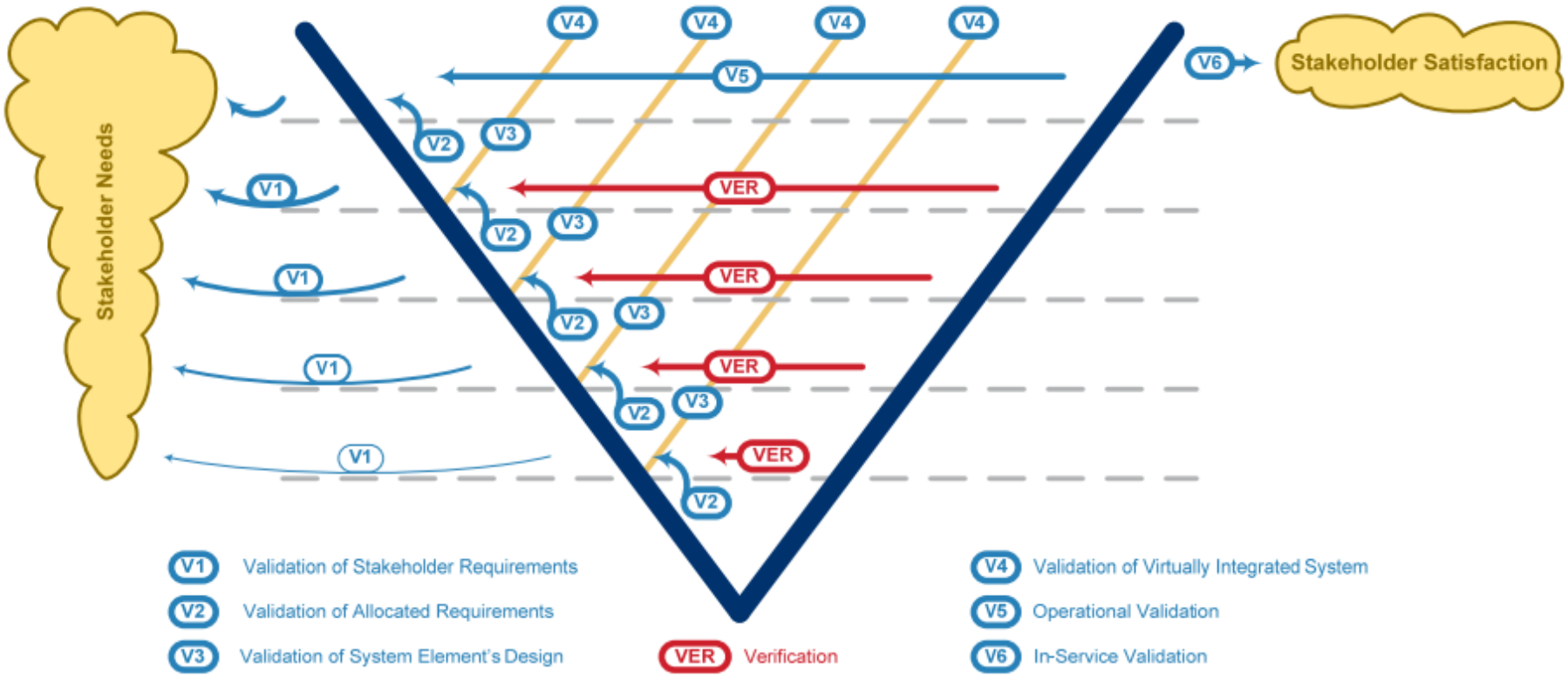


Updating the V-Model



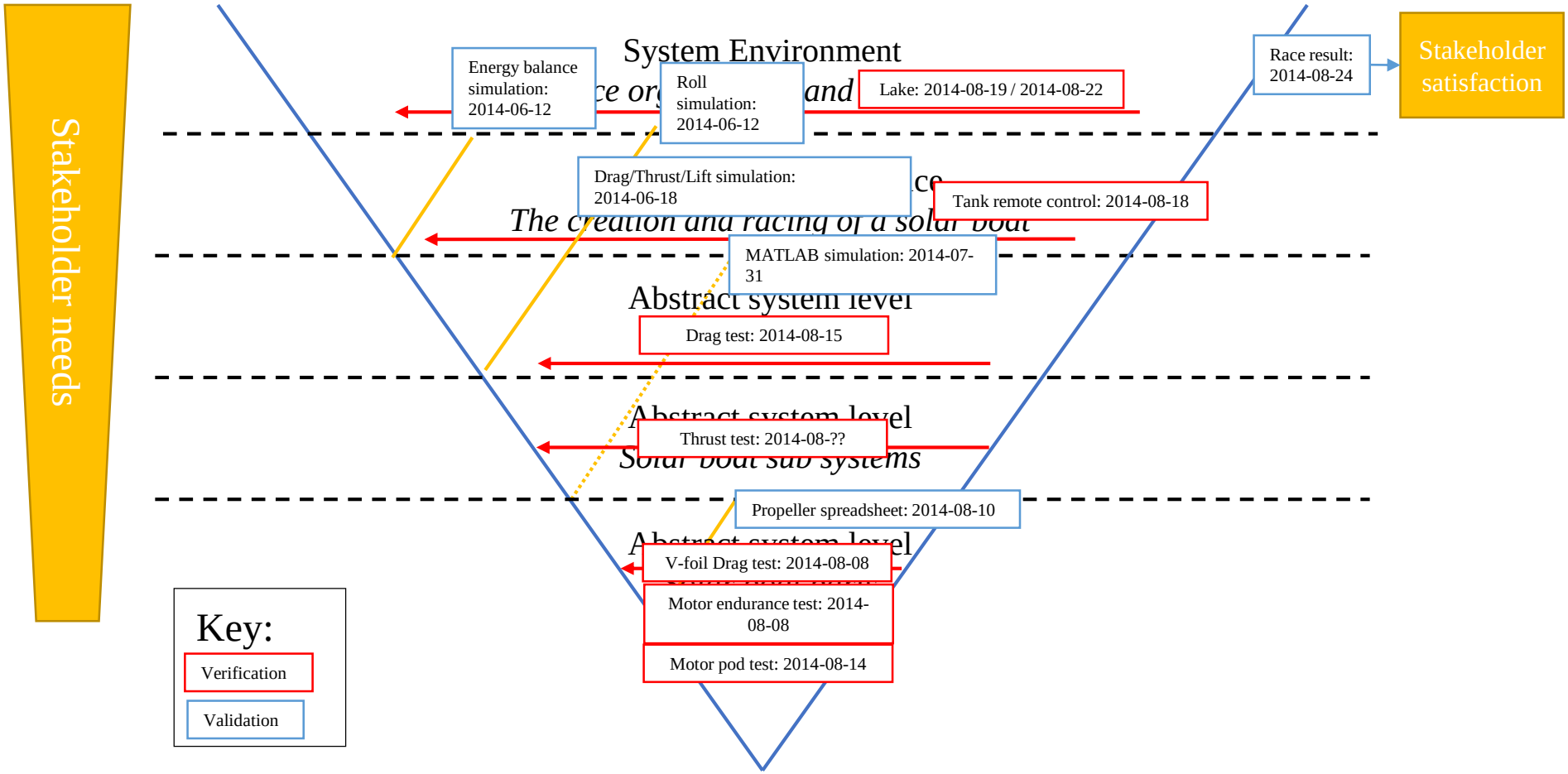
From: Scheithauer and Forsberg, 2013.

Assurance V

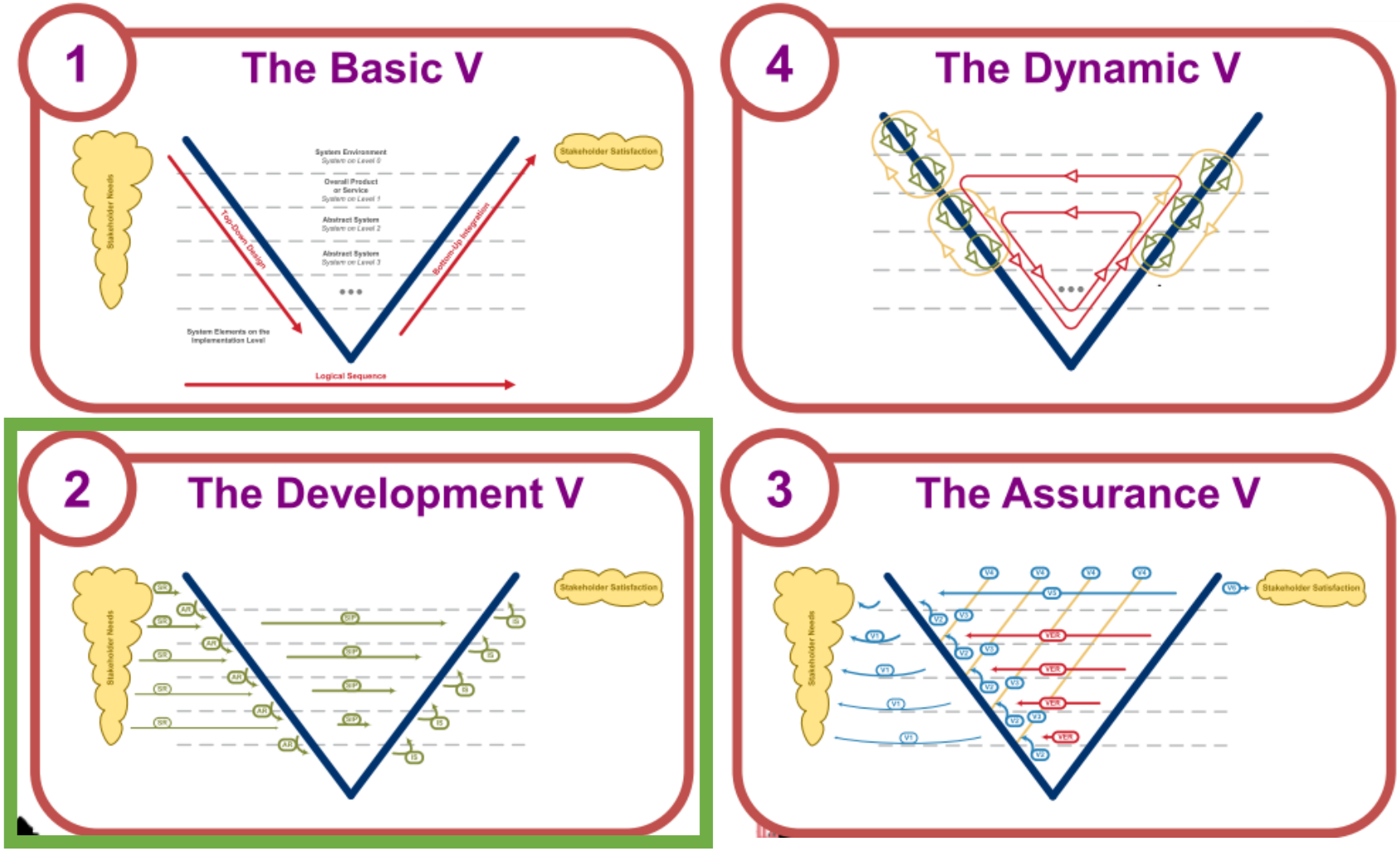


From: Scheithauer and Forsberg, 2013.

Assurance V: SolarBoat 2014

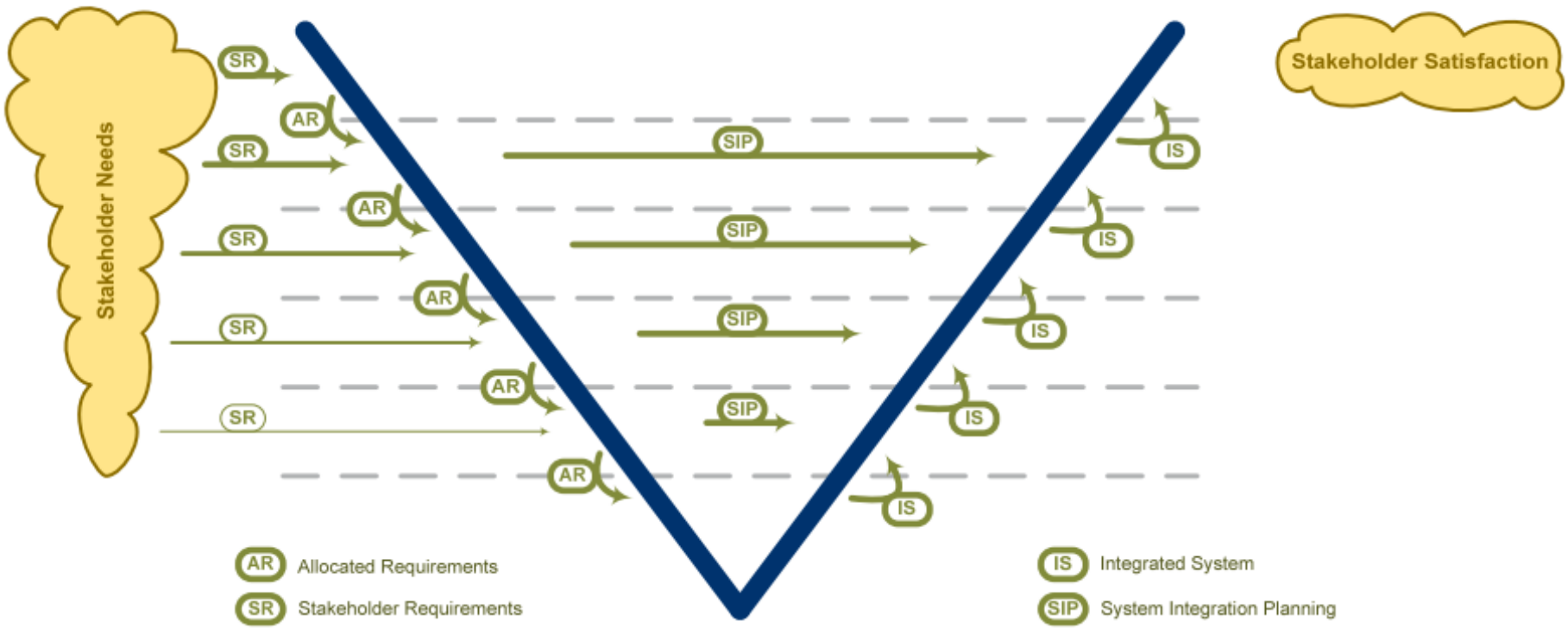


Updating the V-Model



From: Scheithauer and Forsberg, 2013.

Development V

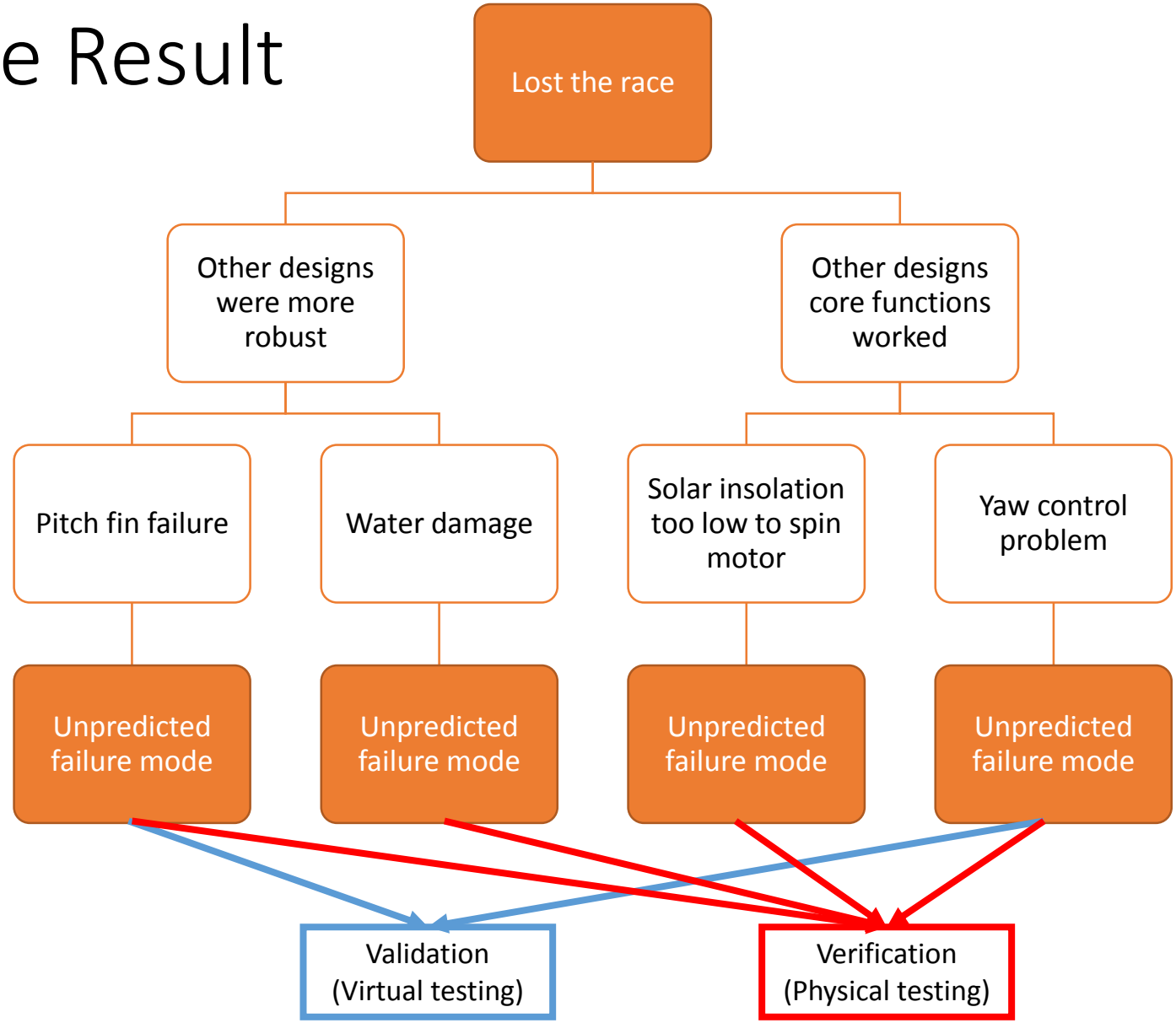


From: Scheithauer and Forsberg, 2013.

Presentation Overview

1. Definitions:
   1. SolarBoat
   2. Systems Engineering
2. SolarBoat 2014 results
3. V-Model to analyse development and determine alternative work
4. **<u>Grouping solutions and building a new development plan</u>**
5. Conclusions

Reflection on SolarBoat 2014: Race Result

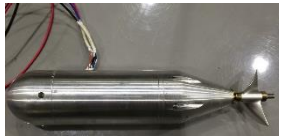


Linking: Work products, Validation and Verification

Verification test

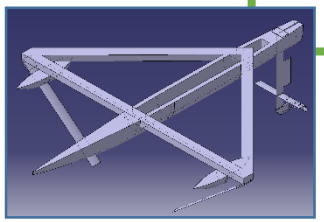
Work Product: Prototype

Work Product: Realized part or sub system



Validation model

Work Product: Design



MATLAB SIMULINK

MODELICA

OMG SYSTEMS MODELING LANGUAGE SysML

Object-Process Methodology

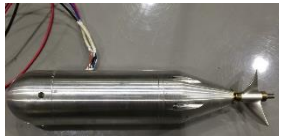
Linking: Work products, Validation and Verification

Verification test

Modelling

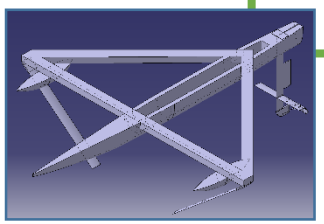
Work Product: Prototype

Work Product: Realized part or sub system



Validation model

Work Product: Design



MATLAB SIMULINK

MODELICA

OMG SYSTEMS MODELING LANGUAGE SysML

Object-Process Methodology

Linking: Work products, Validation and Verification

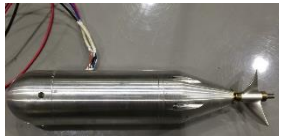
Verification test

Modelling

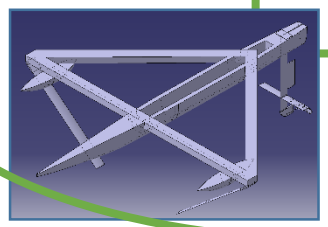
Work Product: Prototype

Validation model

Work Product: Realized part or sub system



Work Product: Design



MATLAB SIMULINK

MODELICA

OMG SYSTEMS MODELING LANGUAGE SysML

Object-Process Methodology

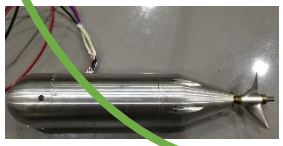
Linking: Work products, Validation and Verification

Verification test

Modelling

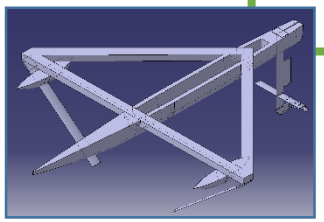
Work Product: Prototype

Work Product: Realized part or sub system



Validation model

Work Product: Design



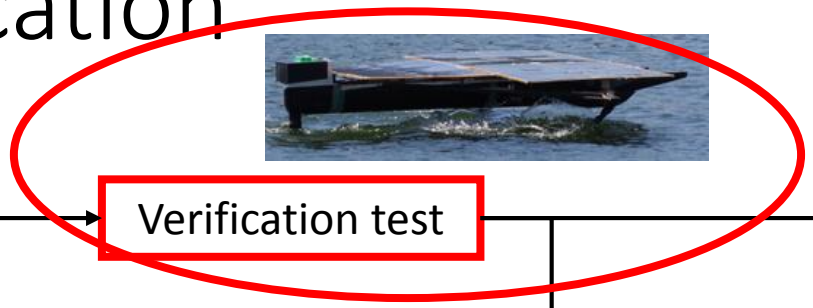
MATLAB SIMULINK

MODELICA

OMG SYSTEMS MODELING LANGUAGE SysML

Object-Process Methodology

Linking: Work products, Validation and Verification



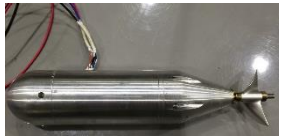
Verification test

Modelling

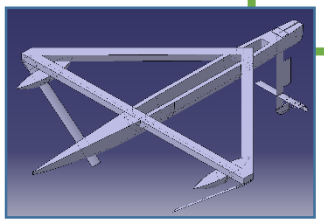
Work Product: Prototype

Validation model

Work Product: Realized part or sub system



Work Product: Design

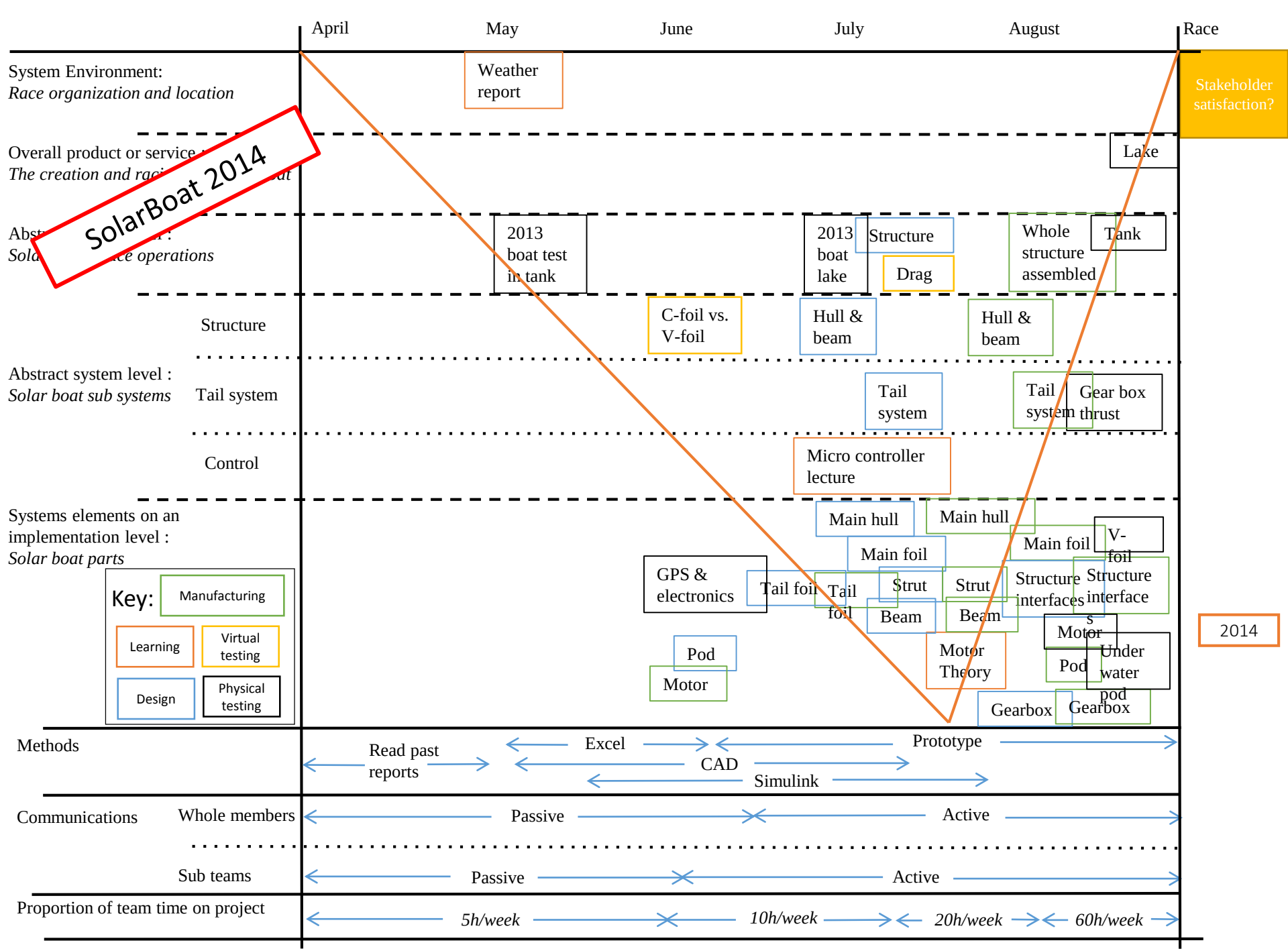


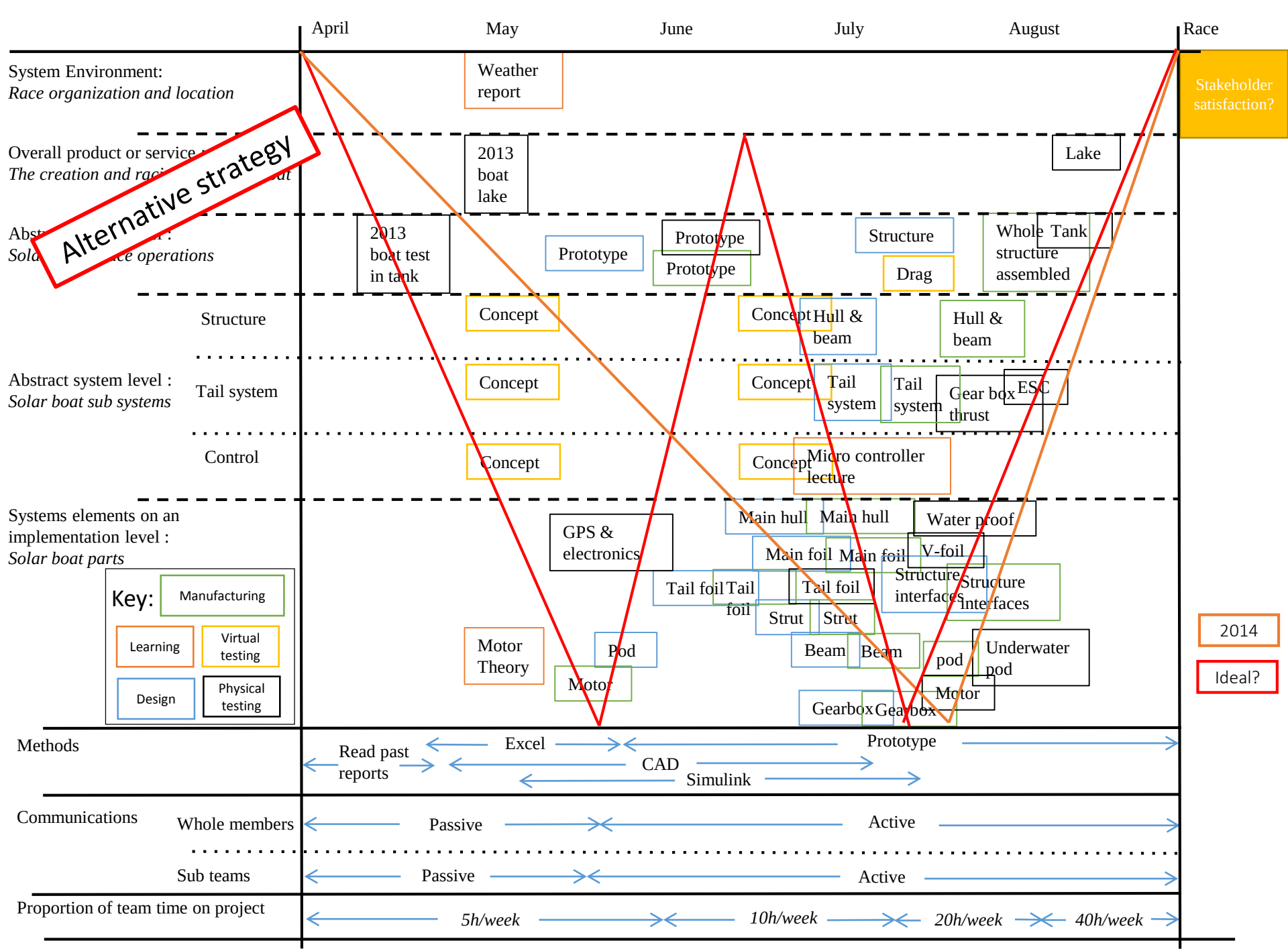
MATLAB SIMULINK

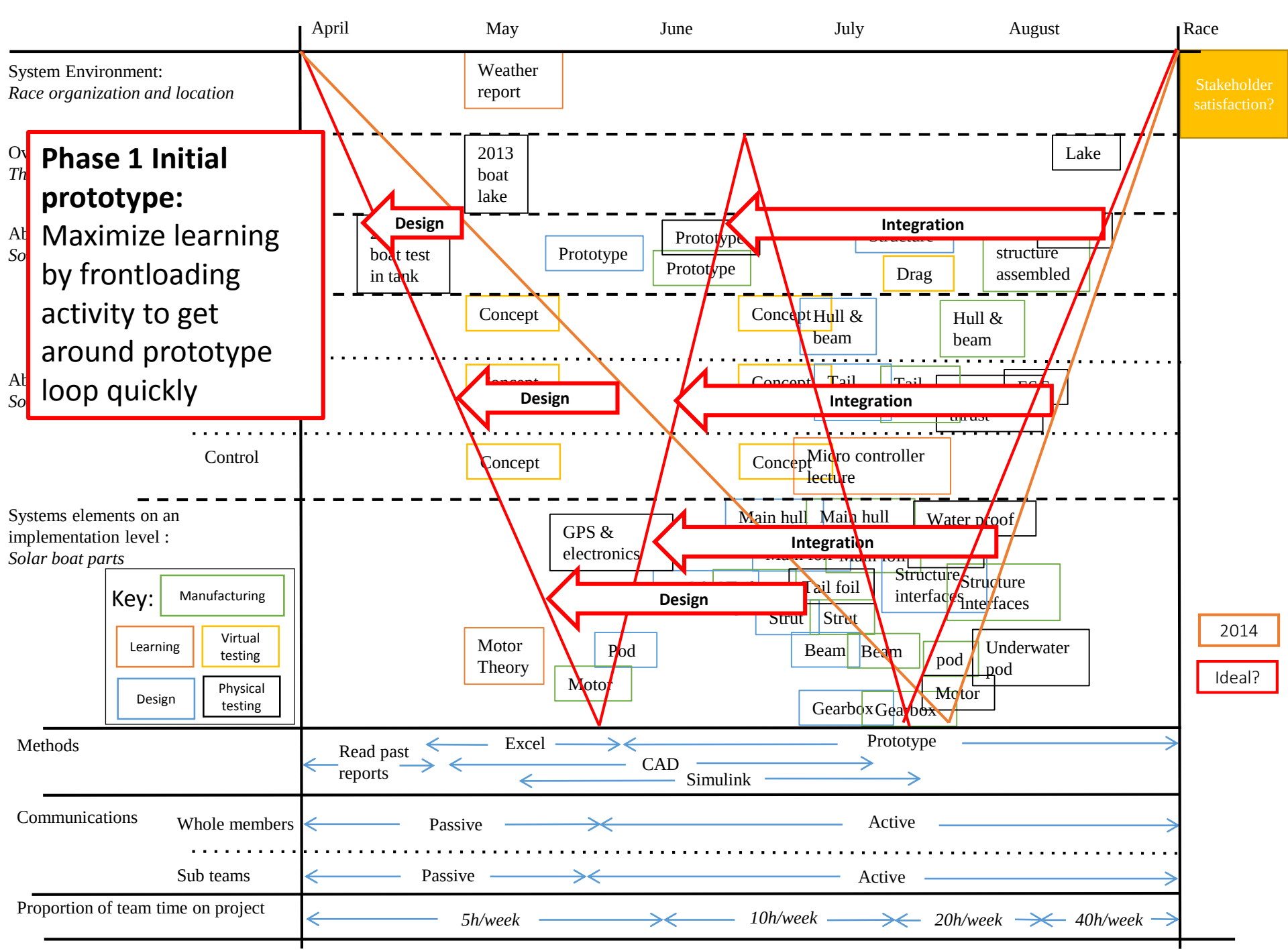
MODELICA

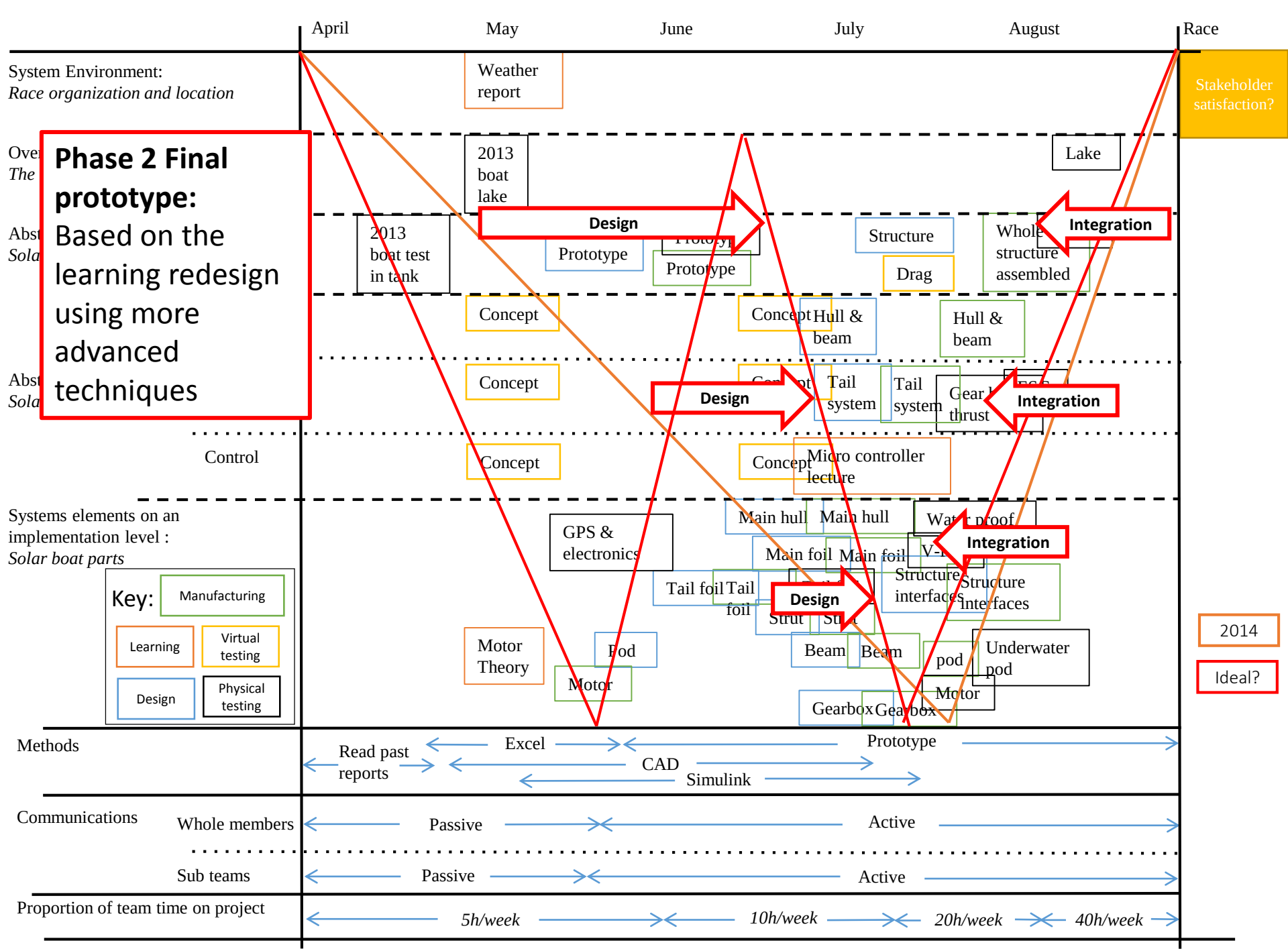
OMG SYSTEMS MODELING LANGUAGE SysML

Object-Process Methodology

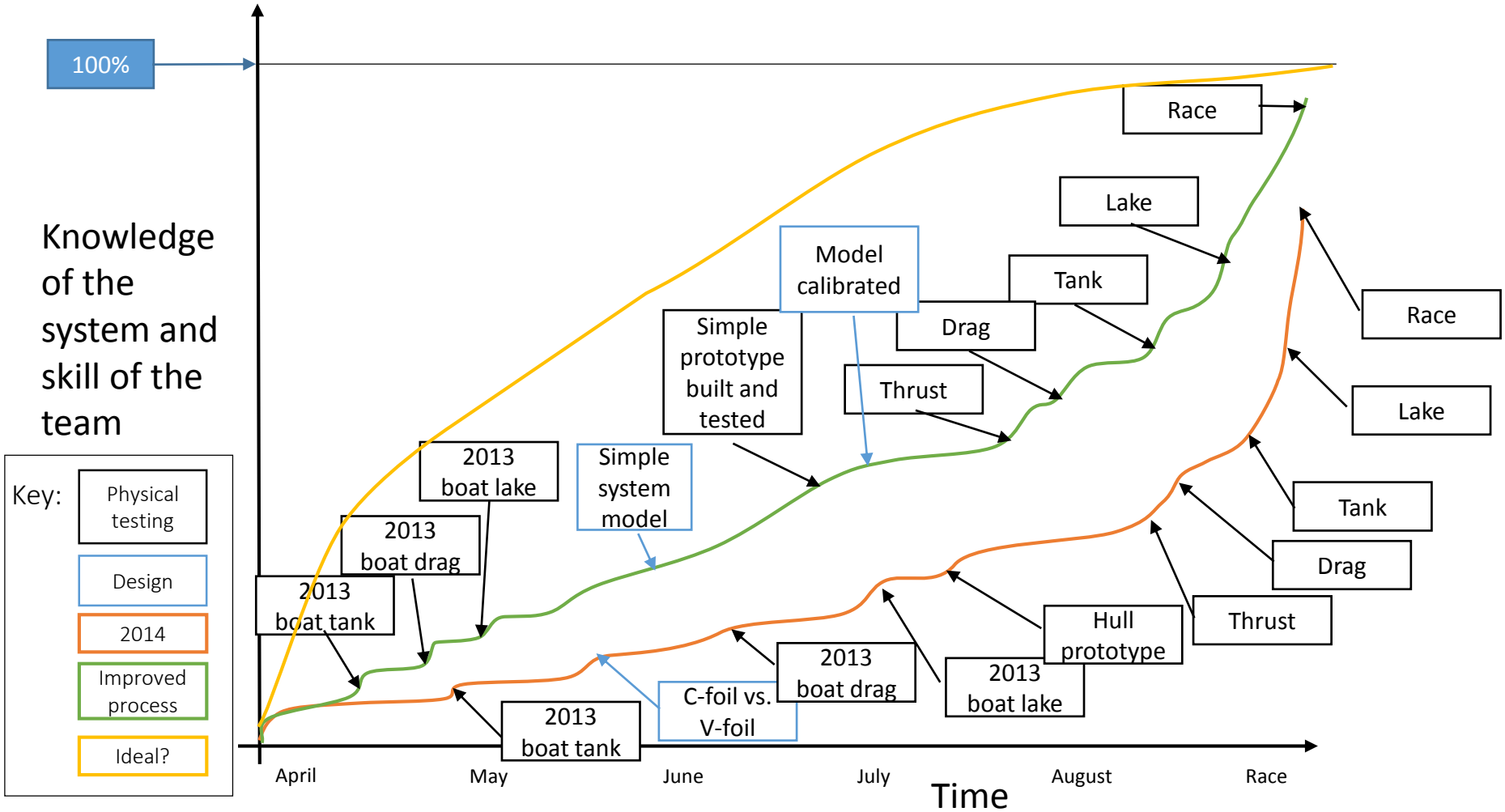

April
May
June
July
August
Race
System Environment:
Race organization and location
Weather report
Stakeholder satisfaction?
Overall product or service :
The creation and racing of a solar boat
Lake
SolarBoat 2014
Abstract system level :
Solar boat operations
2013 boat test in tank
2013 boat lake
Structure
Drag
Whole structure assembled
Tank
Structure
C-foil vs. V-foil
Hull & beam
Hull & beam
Abstract system level :
Solar boat sub systems
Tail system
Tail system
Tail system
Gear box thrust
Control
Micro controller lecture
Systems elements on an implementation level :
Solar boat parts
Main hull
Main hull
Main foil
V-foil
Main foil
GPS & electronics
Tail foil
Tail foil
Strut
Strut
Structure interfaces
Structure interfaces
Beam
Beam
Motor
Pod
Motor
Motor Theory
Pod
Under water pod
Gearbox
Gearbox
Key:
Manufacturing
Learning
Virtual testing
Design
Physical testing
2014
Methods
Read past reports
Excel
CAD
Simulink
Prototype
Communications
Whole members
Passive
Active
Sub teams
Passive
Active
Proportion of team time on project
5h/week
10h/week
20h/week
60h/week


April
May
June
July
August
Race
System Environment:
Race organization and location
Weather report
Stakeholder satisfaction?
Overall product or service :
The creation and racing of a solar boat
2013 boat lake
Lake
Alternative strategy
Abstract system level :
Solar boat operations
2013 boat test in tank
Prototype
Prototype
Prototype
Structure
Drag
Whole structure assembled
Tank
Structure
Concept
Concept
Hull & beam
Hull & beam
Abstract system level :
Solar boat sub systems
Tail system
Concept
Concept
Tail system
Tail system
Gear box thrust
ESC
Control
Concept
Concept
Micro controller lecture
Systems elements on an implementation level :
Solar boat parts
GPS & electronics
Main hull
Main hull
Water proof
Main foil
Main foil
V-foil
Tail foil
Tail foil
Tail foil
Structure interfaces
Structure interfaces
Strut
Strut
Motor Theory
Pod
Motor
Beam
Beam
pod
Underwater pod
Motor
Gearbox
Gearbox
Key:
Manufacturing
Learning
Virtual testing
Design
Physical testing
2014
Ideal?
Methods
Read past reports
Excel
CAD
Simulink
Prototype
Communications
Whole members
Passive
Active
Sub teams
Passive
Active
Proportion of team time on project
5h/week
10h/week
20h/week
40h/week


April
May
June
July
August
Race
System Environment:
Race organization and location
Weather report
Stakeholder satisfaction?
Phase 1 Initial prototype:
Maximize learning by frontloading activity to get around prototype loop quickly
2013 boat lake
Lake
Design
Integration
boat test in tank
Prototype
Prototype
Prototype
Drag
structure assembled
Concept
Concept
Hull & beam
Hull & beam
Design
Integration
Control
Concept
Concept
Micro controller lecture
Systems elements on an implementation level :
Solar boat parts
GPS & electronics
Main hull
Main hull
Water proof
Integration
Design
Tail foil
Structure interfaces
Structure interfaces
Strut
Strut
Motor Theory
Pod
Motor
Beam
Beam
pod
Underwater pod
Motor
Gearbox
Gearbox
Key:
Manufacturing
Learning
Virtual testing
Design
Physical testing
2014
Ideal?
Methods
Read past reports
Excel
CAD
Simulink
Prototype
Communications
Whole members
Passive
Active
Sub teams
Passive
Active
Proportion of team time on project
5h/week
10h/week
20h/week
40h/week

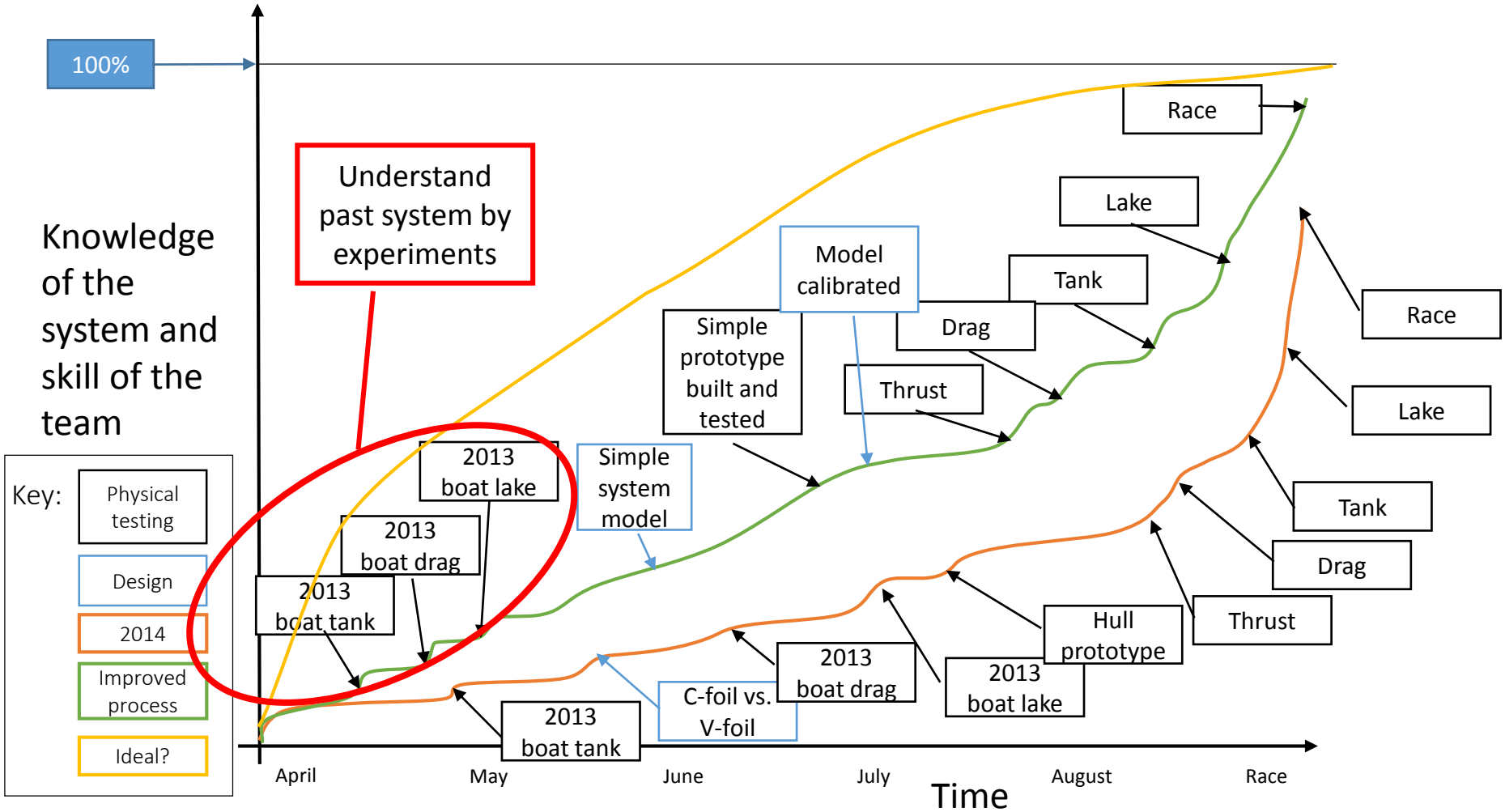

April
May
June
July
August
Race
System Environment:
Race organization and location
Weather report
Stakeholder satisfaction?
Phase 2 Final prototype:
Based on the learning redesign using more advanced techniques
2013 boat lake
Lake
2013 boat test in tank
Design
Prototype
Prototype
Structure
Drag
Whole structure assembled
Integration
Concept
Concept
Hull & beam
Hull & beam
Concept
Design
Tail system
Tail system
Gear thrust
Integration
Control
Concept
Concept
Micro controller lecture
Systems elements on an implementation level :
Solar boat parts
GPS & electronics
Main hull
Main hull
Main foil
Main foil
Integration
Tail foil
Tail foil
Design
Structure interfaces
Structure interfaces
Strut
Motor Theory
Pod
Motor
Beam
Beam
pod
Underwater pod
Motor
Gearbox
Gearbox
Key:
Manufacturing
Learning
Virtual testing
Design
Physical testing
2014
Ideal?
Methods
Read past reports
Excel
CAD
Simulink
Prototype
Communications
Whole members
Passive
Active
Sub teams
Passive
Active
Proportion of team time on project
5h/week
10h/week
20h/week
40h/week

Knowledge / Skill Growth curve: Alternative strategy



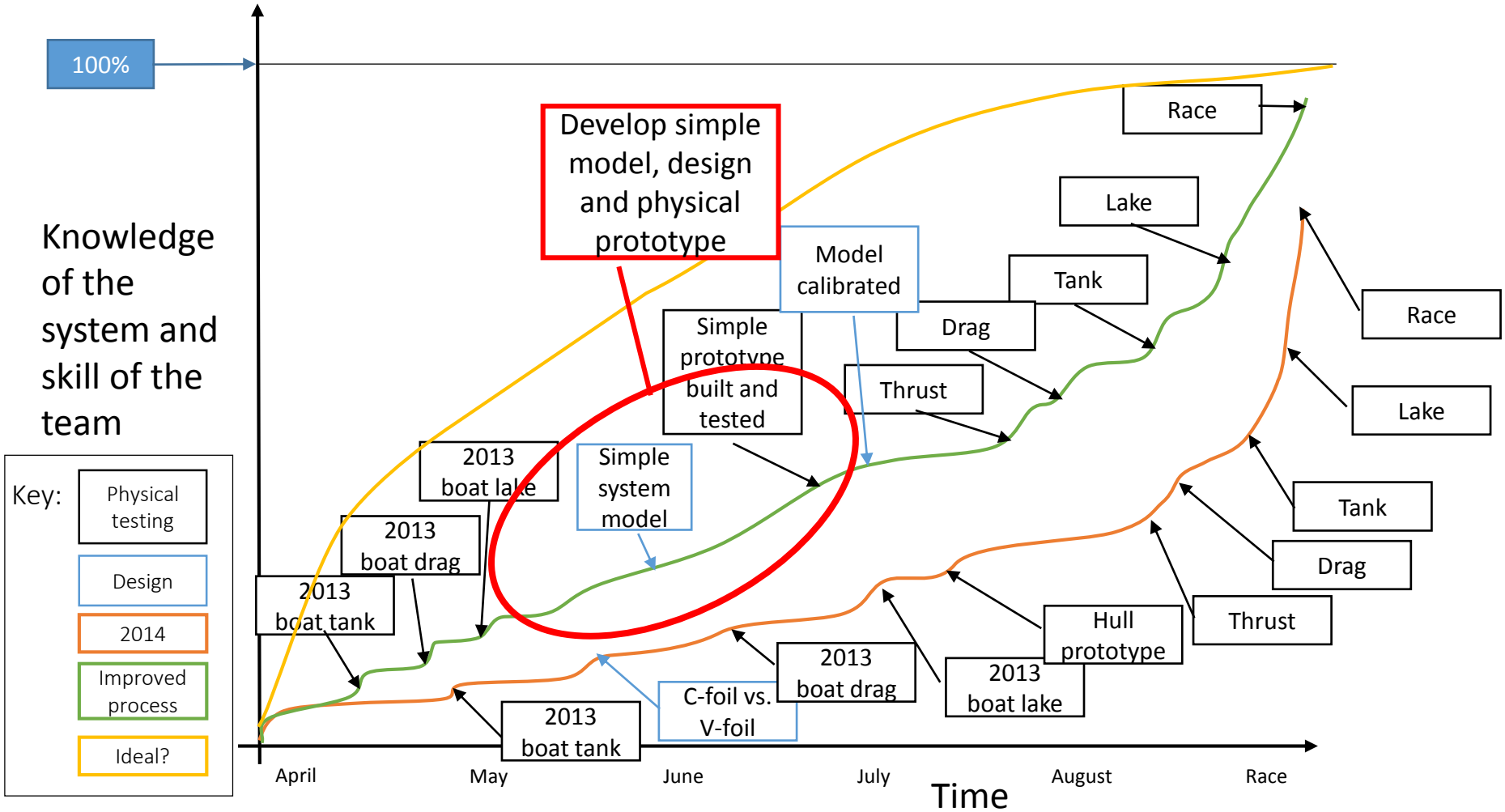
Adapted from model proposed in: Scheithauer 2012

Knowledge / Skill Growth curve: Alternative strategy



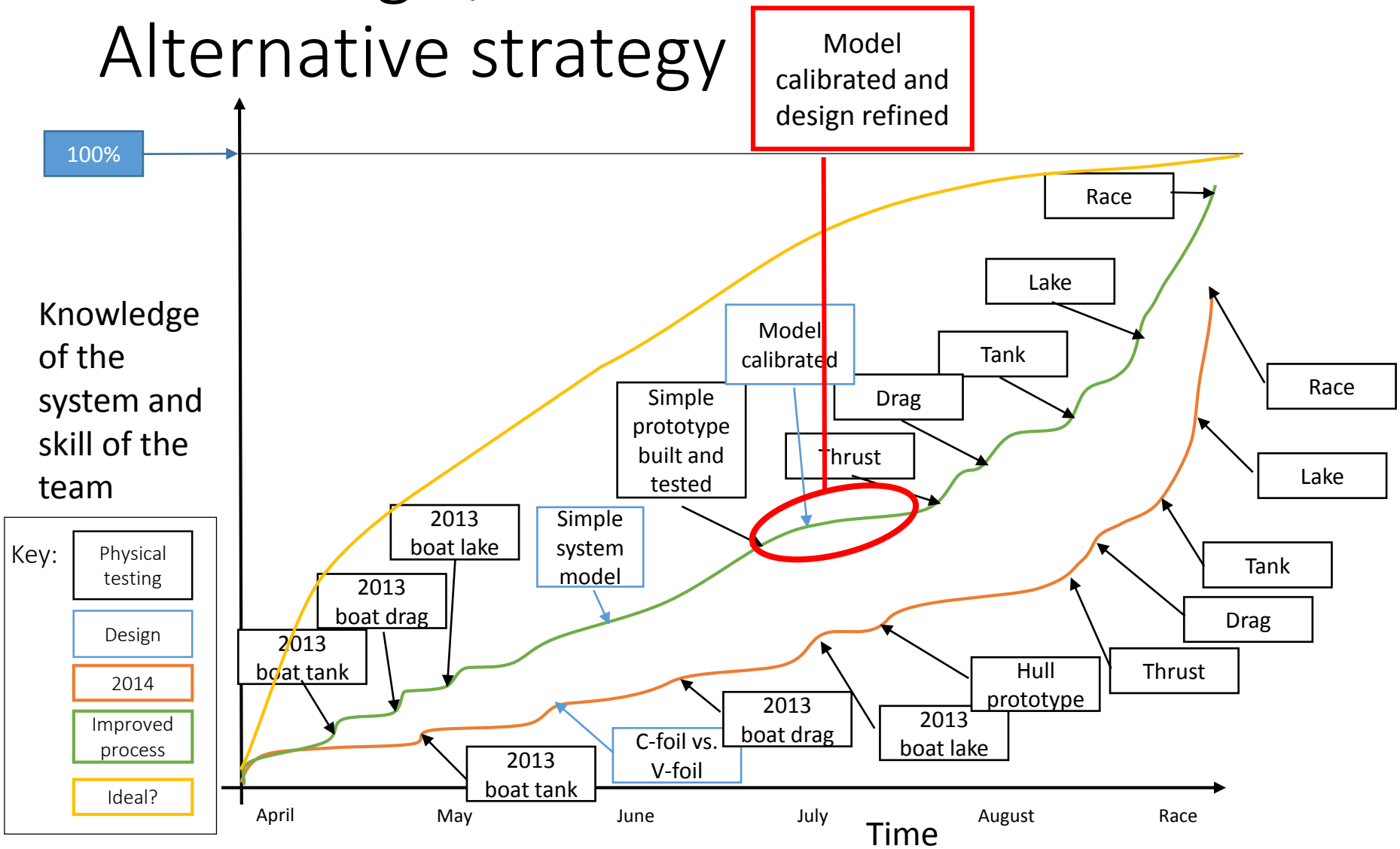
Adapted from model proposed in: Scheithauer 2012

Knowledge / Skill Growth curve: Alternative strategy



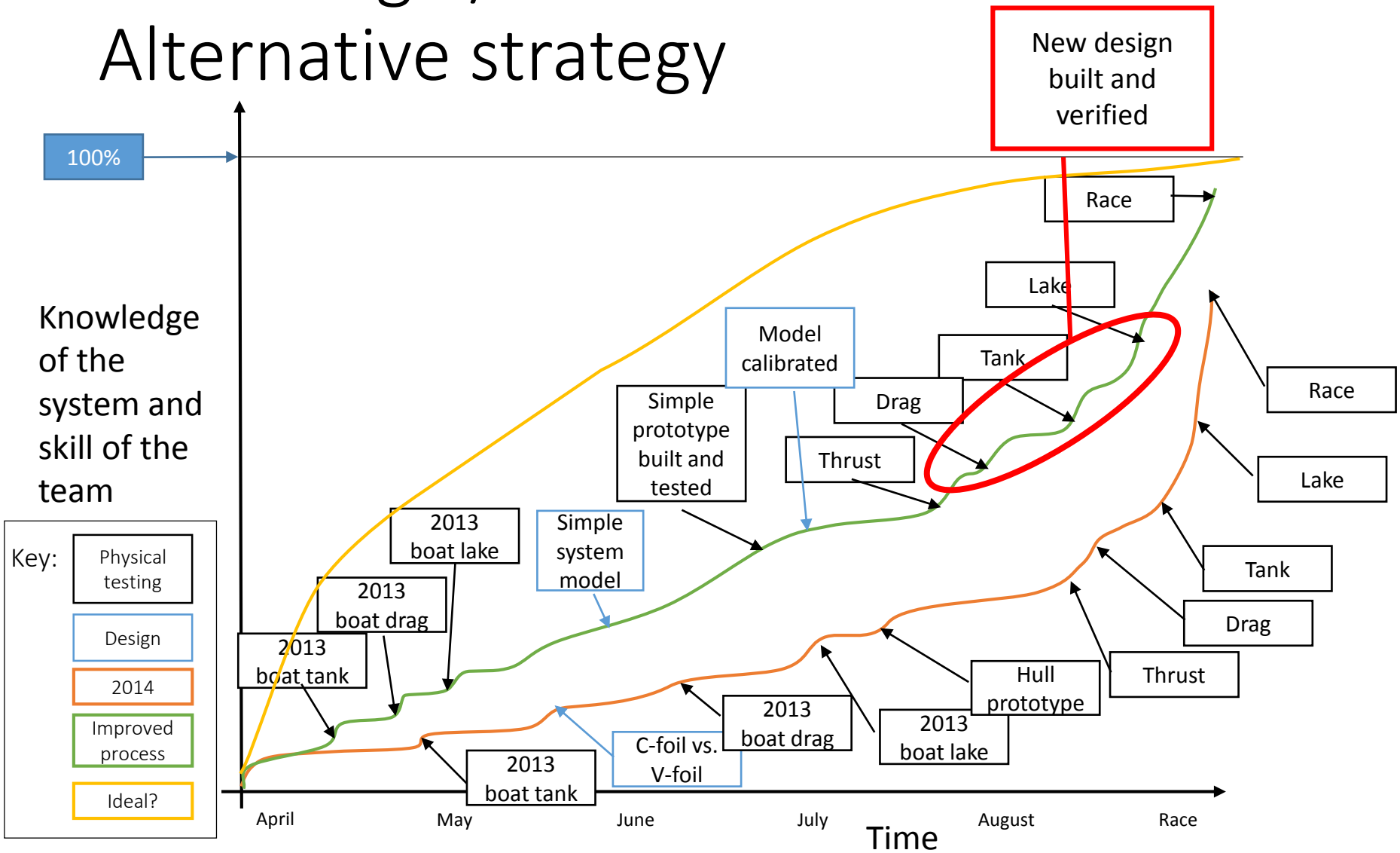
Adapted from model proposed in: Scheithauer 2012

Knowledge / Skill Growth curve: Alternative strategy



Adapted from model proposed in: Scheithauer 2012

Knowledge / Skill Growth curve: Alternative strategy



Adapted from model proposed in: Scheithauer 2012

Presentation Overview

1. Definitions:
   1. SolarBoat
   2. Systems Engineering
2. SolarBoat 2014 results
3. V-Model to analyse development and determine alternative work
4. Grouping solutions and building a new development plan
5. **<u>Conclusions</u>**

Product development process improvements

- As per Scheithauer 2012 **"iterations are the rule in systems engineering, not the exceptions."**
- **Appreciation of knowledge** and skill should drive decisions
- Using the four V-Model views forces a team to think **what work products are needed** and ensure they are **tested**
- **Validated modeling** can avoid rework cycles

Conclusions

- The **four V-Model views** were an **effective** way to present development activity
- **Knowledge Growth Curve** was effective way of communicating the difficulties experienced on the project
- **Significant disconnect** between the project and what industry recognizes as being effective

Future research

- **V-Model views** were made retrospectively, investigate effectiveness **during active development**
- **Modeling** is required early in the development program. **Increasing the speed** at which **models can be created**
- How to most effectively and efficiently **teach System Engineering best practices** to appropriate stakeholders

References

- Frithiof N., Lindh E., Sundberg K., Ekelöw J., Lake H. and Ericson M., 2013 P.1217 Final report v1.0 Project ÆGIR: A SOLAR POWERED AUTONOMOUS RACE CRAFT
- INCOSE, “INCOSE - What is System Engineering?,” 14-Jun-2004. [Online]. Available: http://www.incose.org/practice/whatissystemseng.aspx. [Accessed: 07-Dec-2014].
- INCOSE, *Systems Engineering Handbook: A guide for system life cycle processes and activities*, v3.2.2 ed. International Council of Systems Engineering, 2011.
- Scheithauer D., “Managing Concurrency in Systems Engineering,” *INCOSE International Symposium*, vol. 22, no. 1, pp. 2016–2030, 2012.
- Scheithauer D. and Forsberg K., “V-Model Views,” *INCOSE International Symposium*, vol. 23, no. 1, pp. 502–516, 2013.

Acknowledgements and thanks

- This work could not have been completed without the hard work and support of those involved in the Tokyo and KTH SolarBoat teams

http://solarboat.sys.t.u-tokyo.ac.jp/ http://www.kthnavaldesign.se/kth-solar-2014

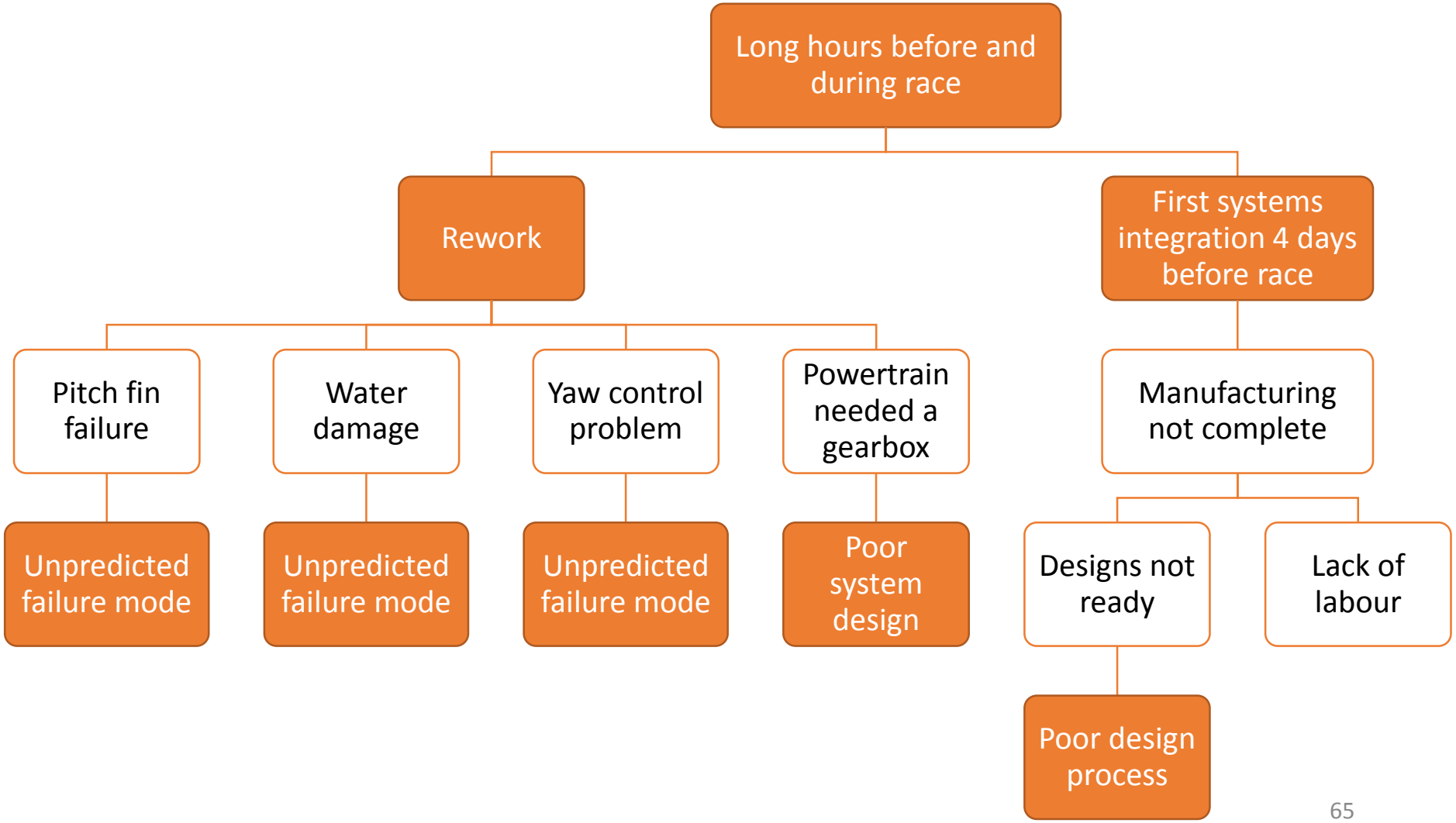
Any questions?

joshua@m.sys.t.u-tokyo.ac.jp

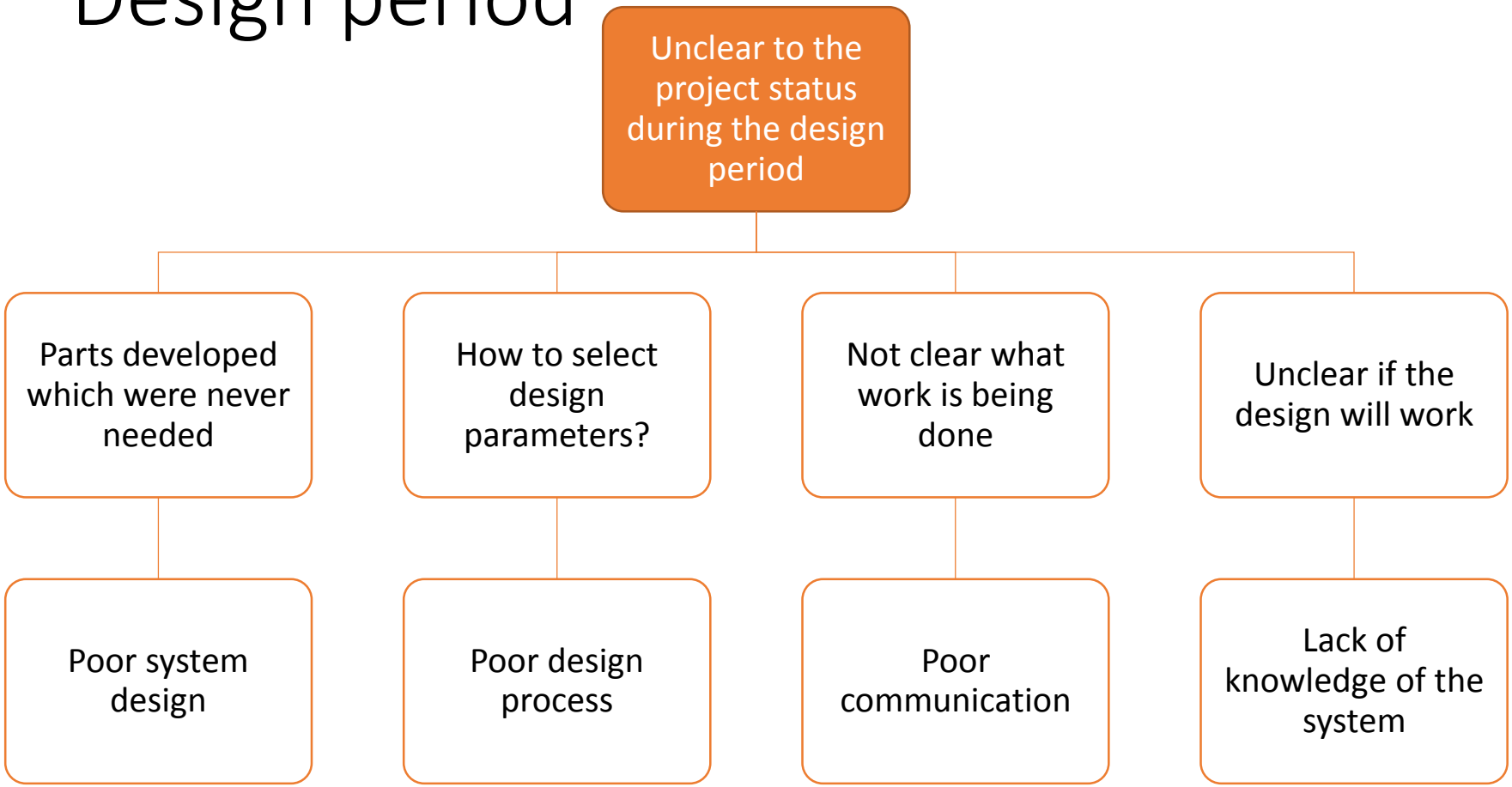
Systems Engineering and the V-Model:
Lessons from an Autonomous Solar Powered Hydrofoil

Extra

Reflection on SolarBoat 2014: Race and just prior

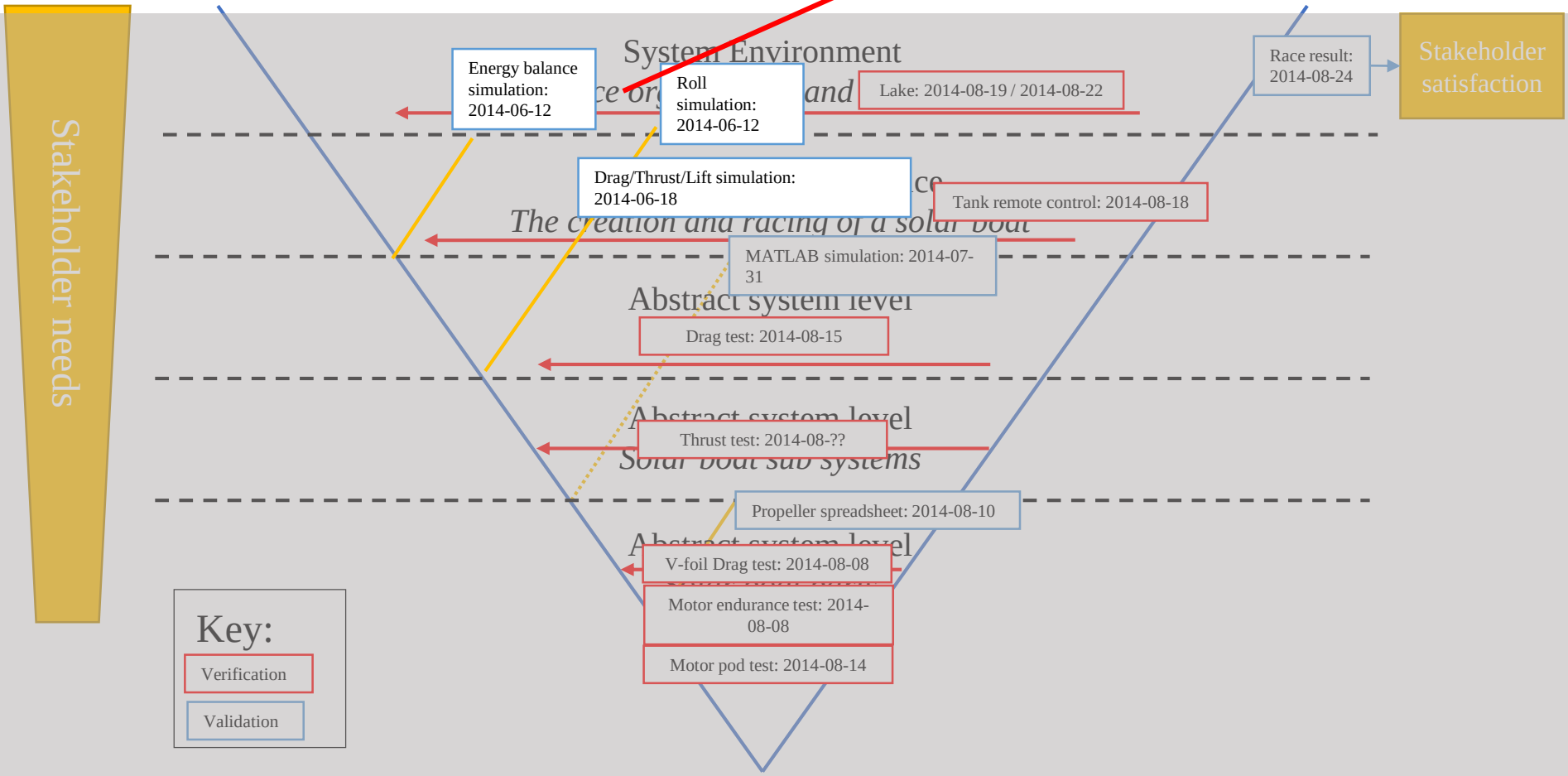


Reflection on SolarBoat 2014: Design period



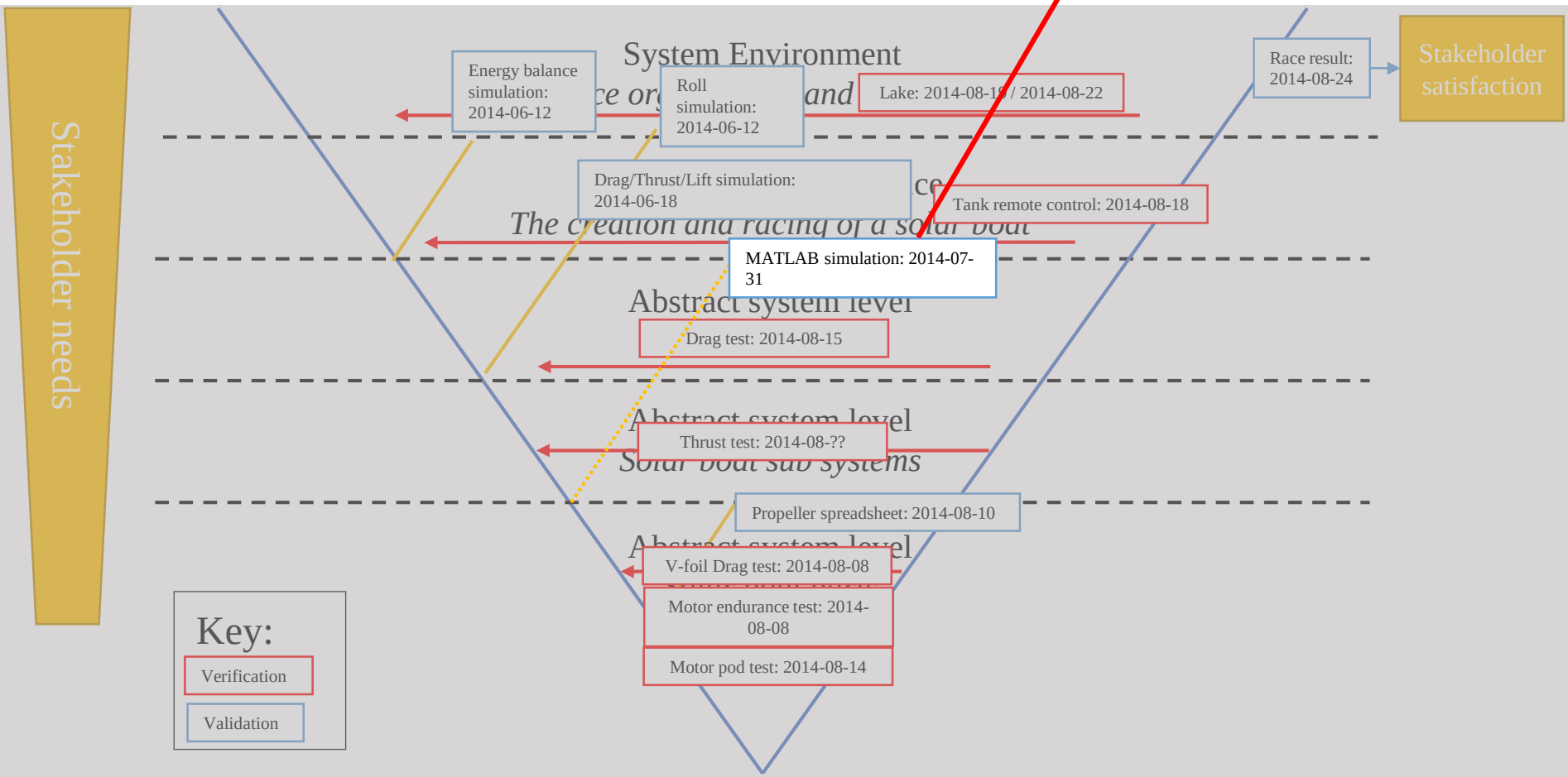
Assurance V: SolarBoat 2014

Good simulation done at a high level but lacked understanding all part inefficiencies



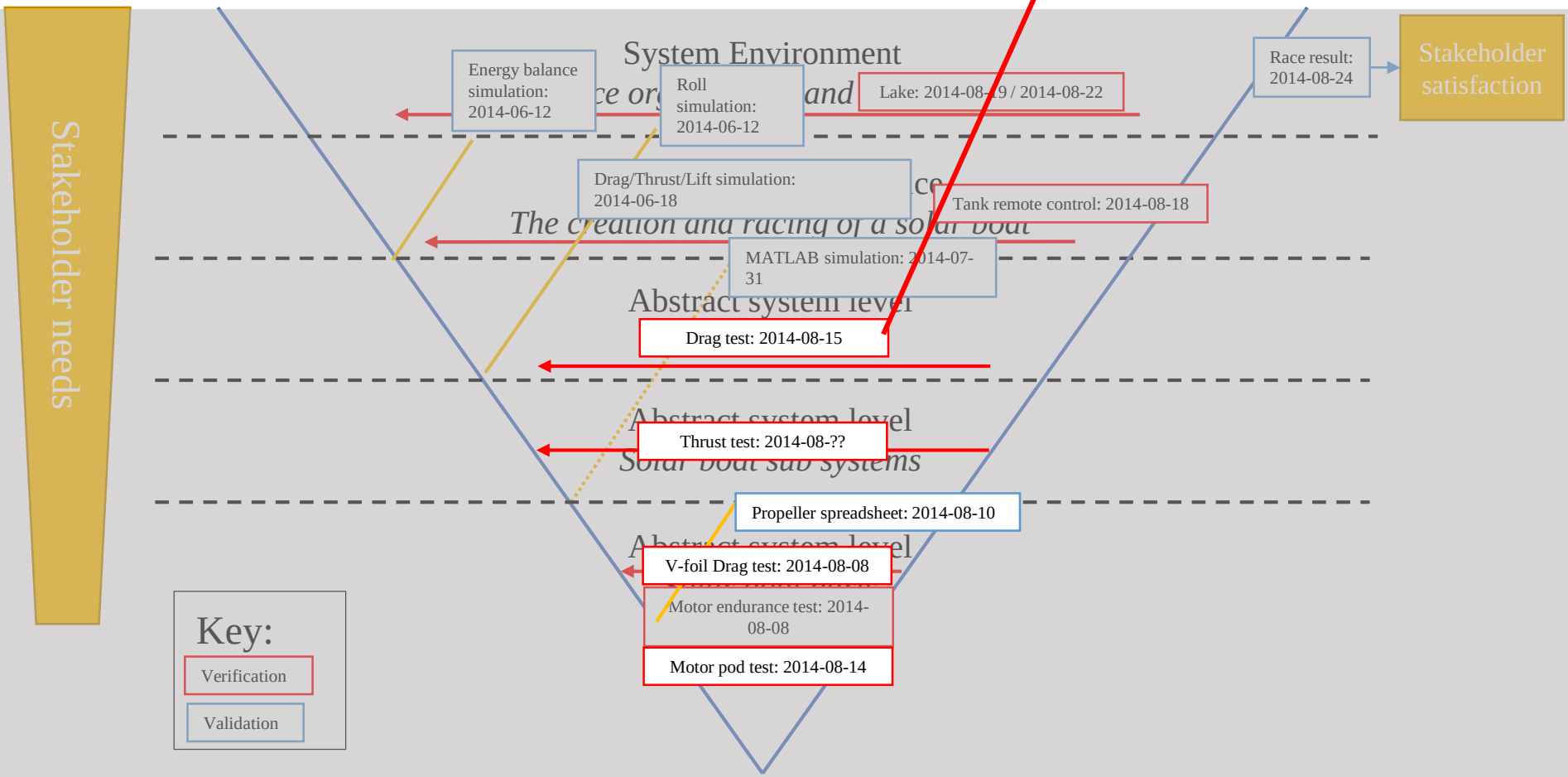
Assurance V: SolarBoat 2014

MATLAB simulation created but lacked verification



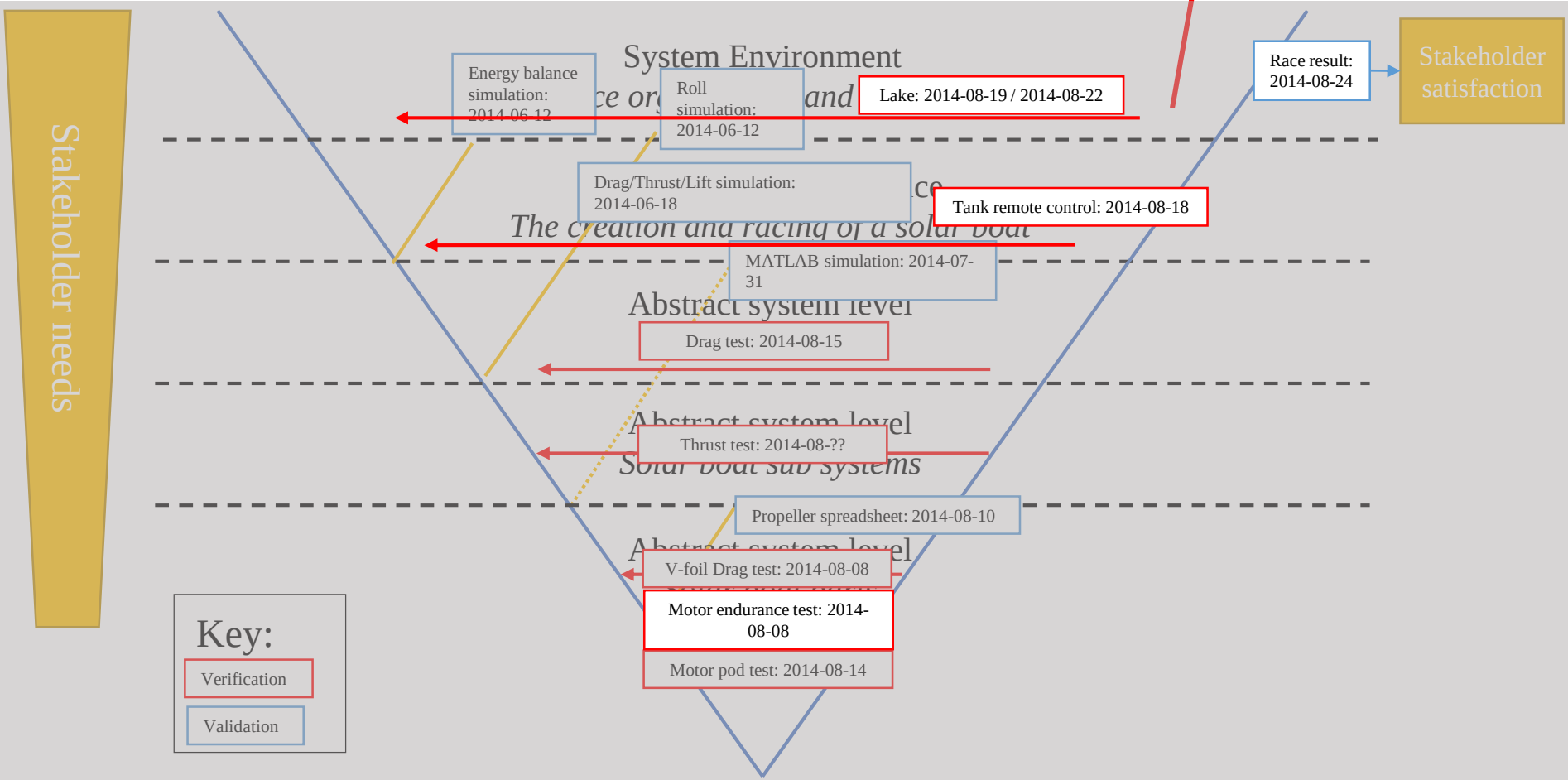
Assurance V: SolarBoat 2014

Experiments for data gathering completed near to the race. No time to change designs



Assurance V: SolarBoat 2014

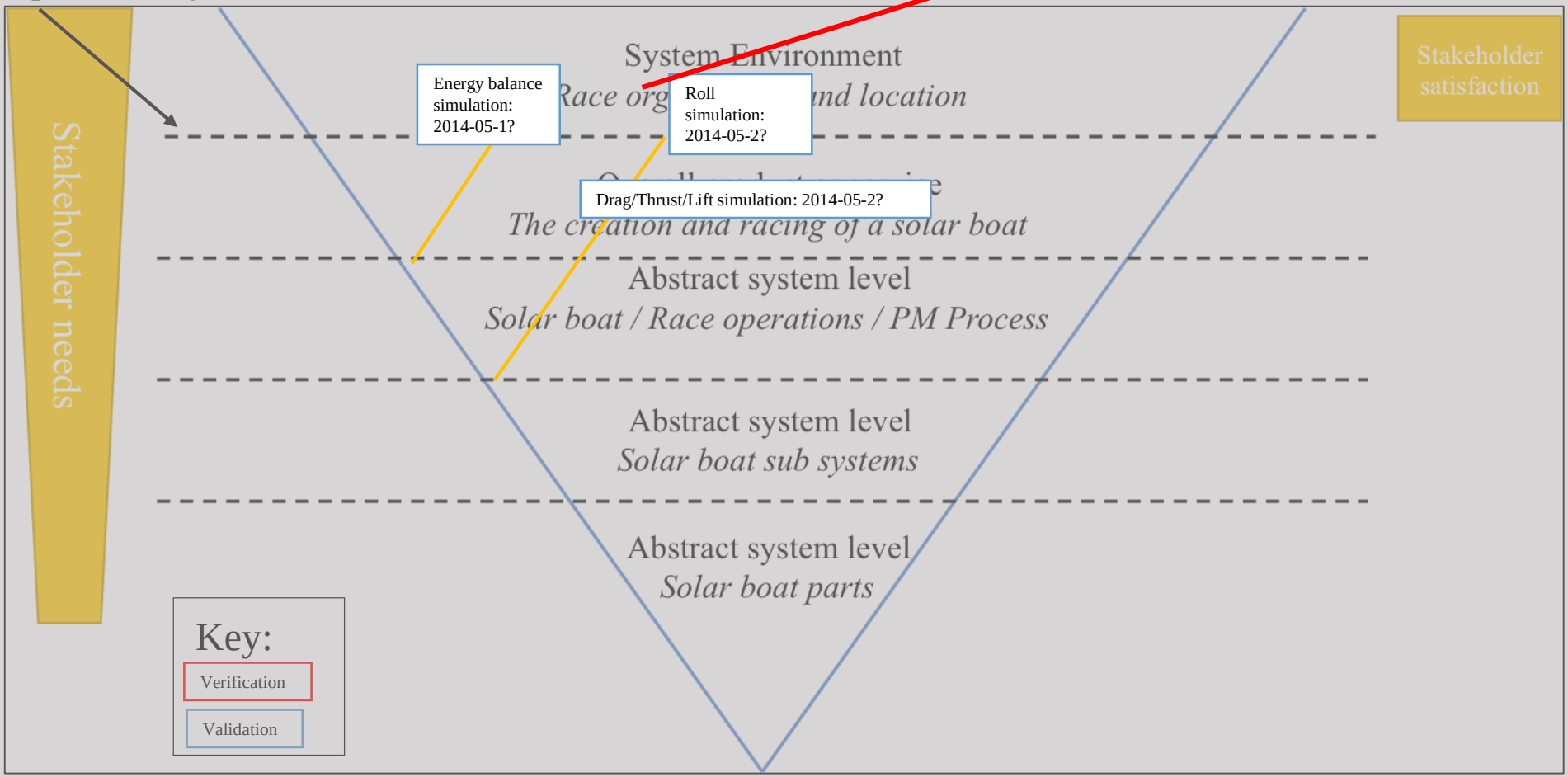
Full system verification test conducted very close to race



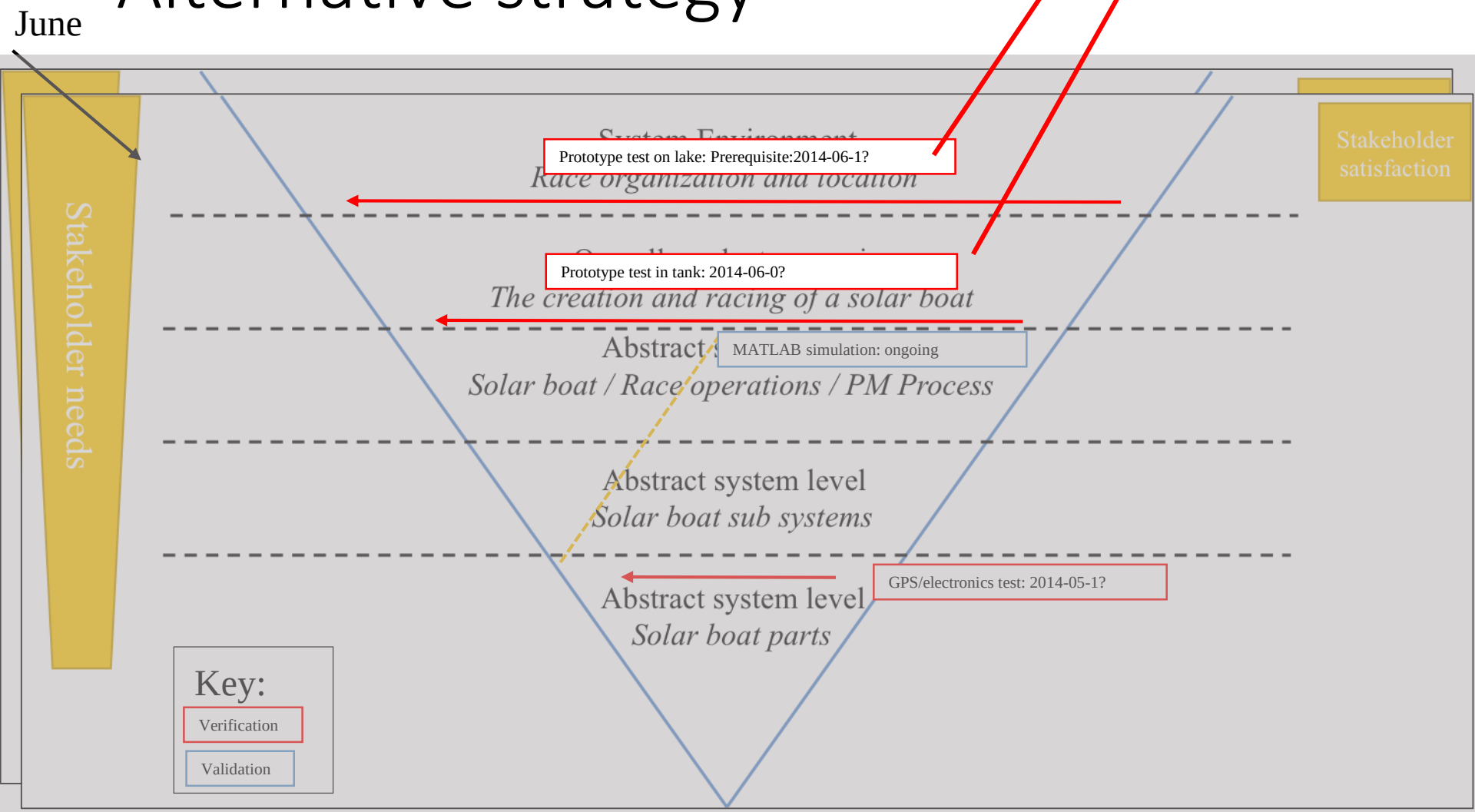
Assurance V: Alternative strategy

Similar energy balances but include all powertrain components

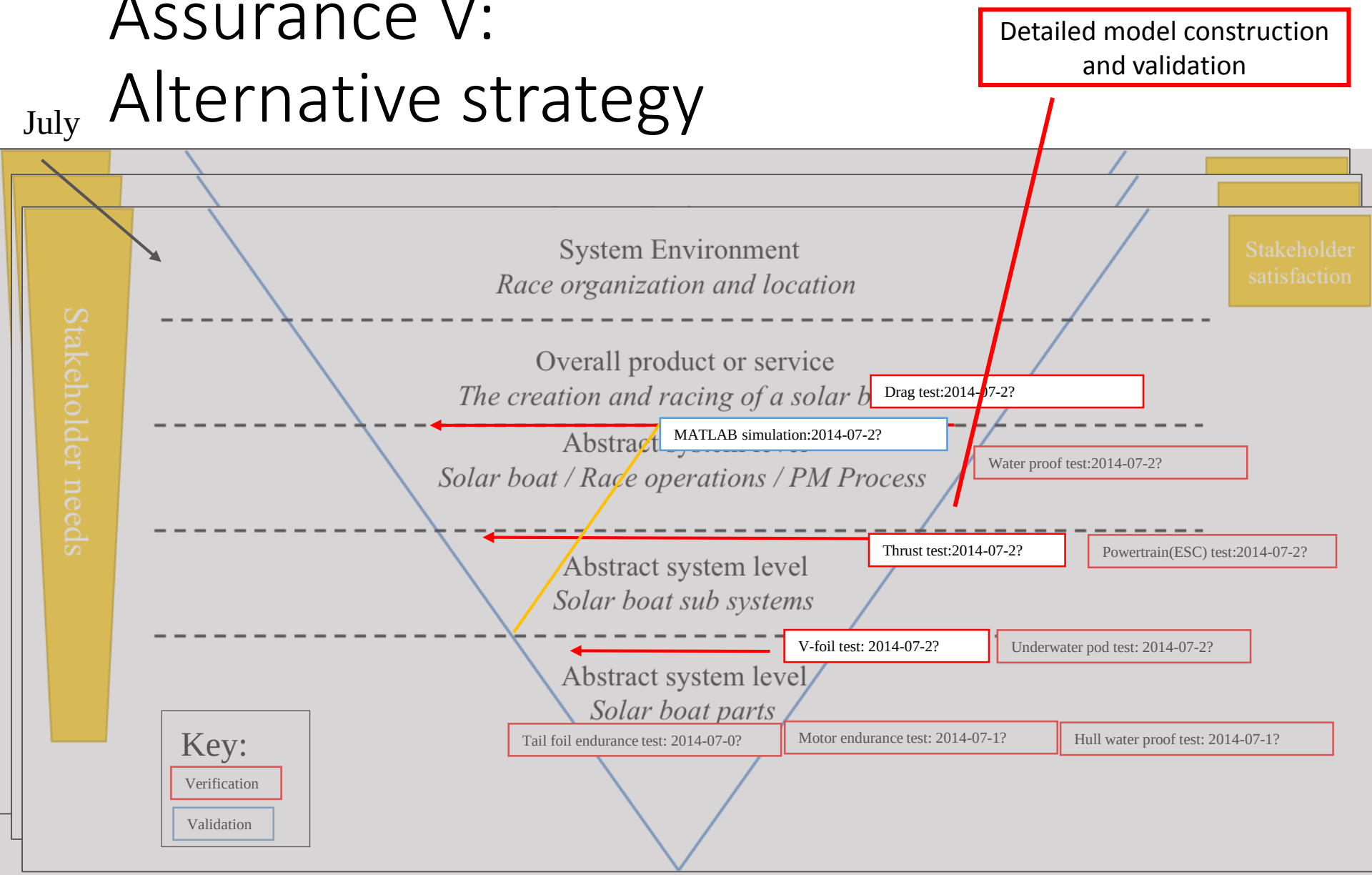
April & May



Assurance V: Alternative strategy



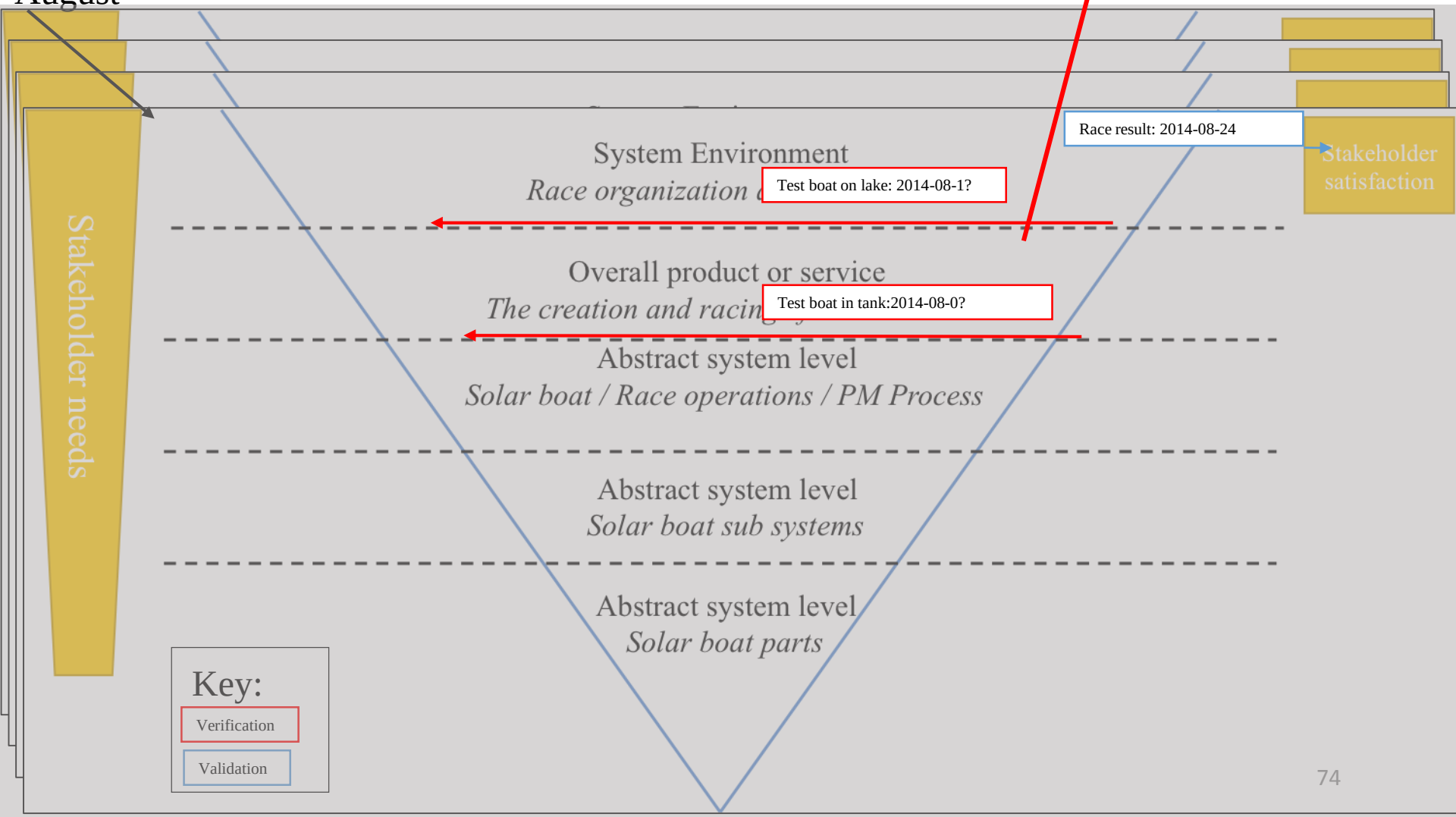
Assurance V: Alternative strategy



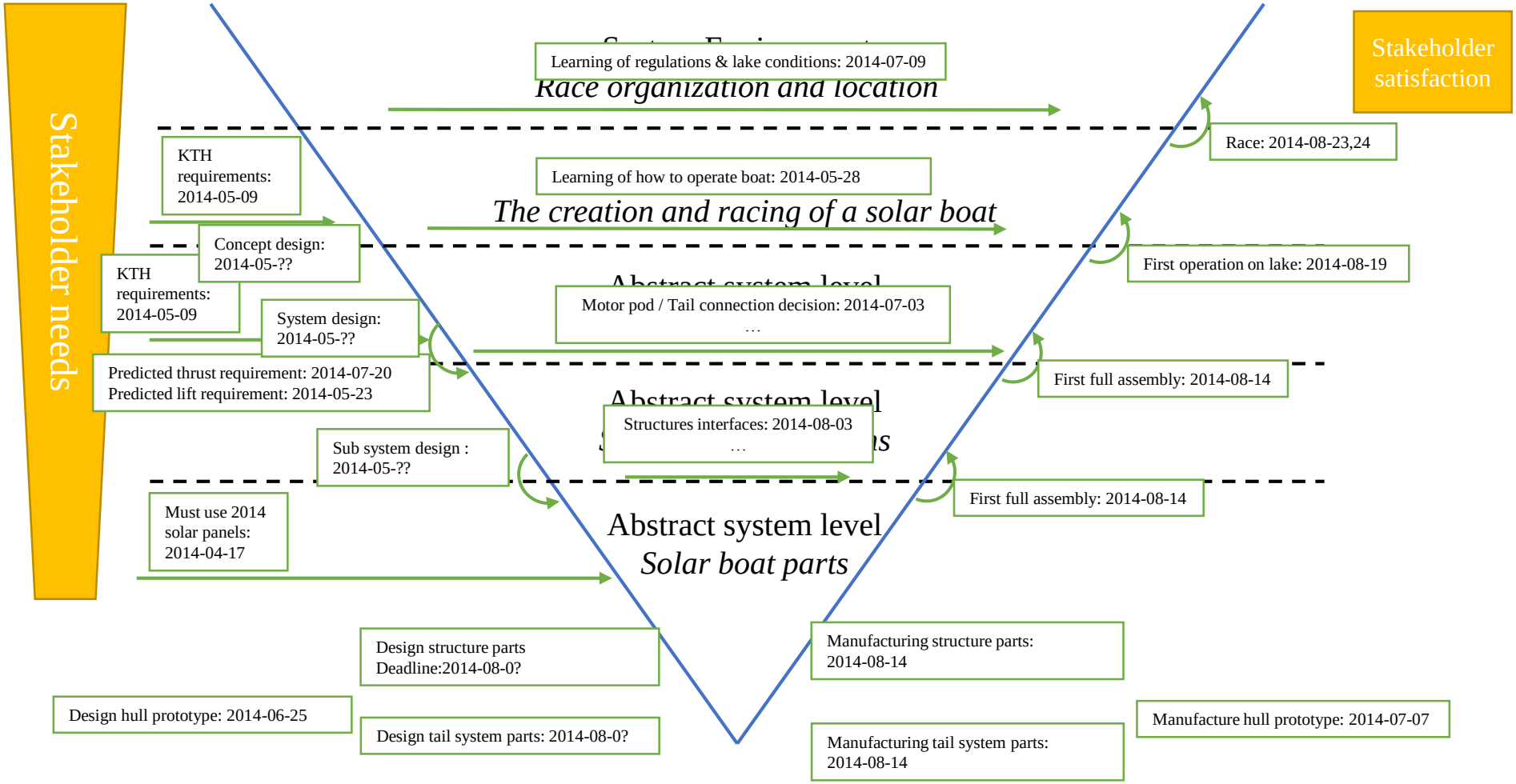
Assurance V: Alternative strategy

Verification of final design.

August

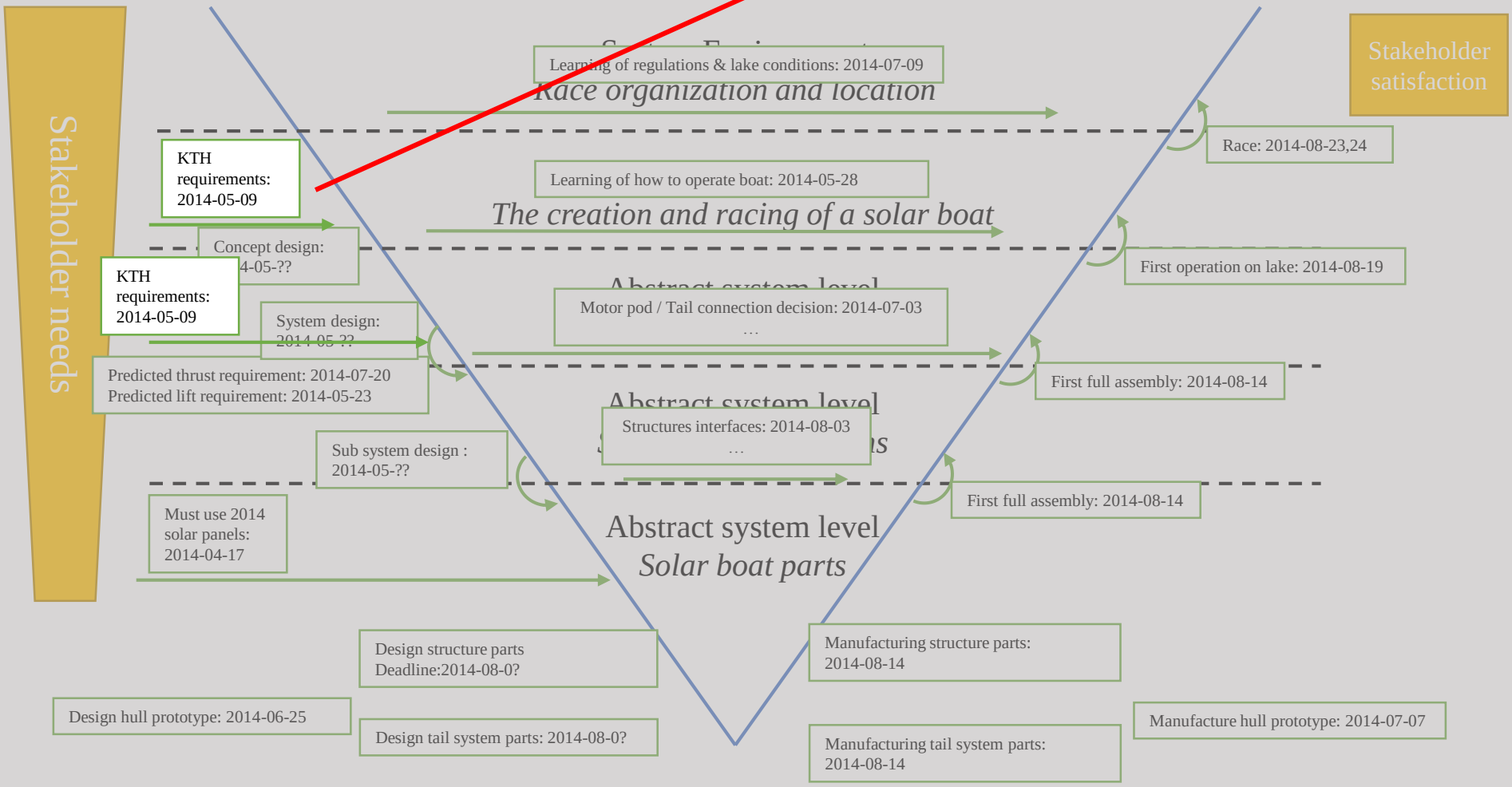


Development V: SolarBoat 2014



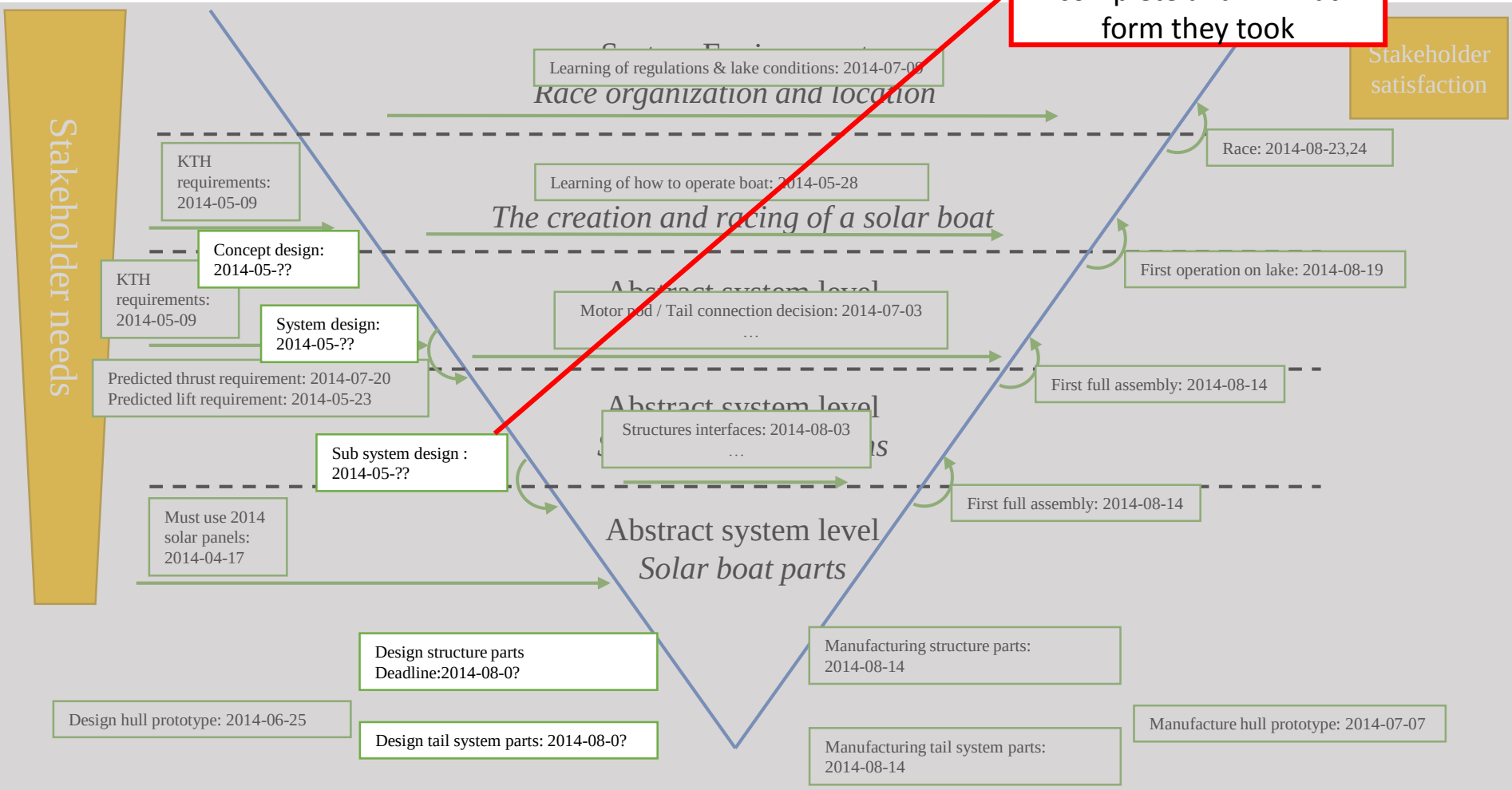
Development V: SolarBoat 2014

Requirements which were never validated



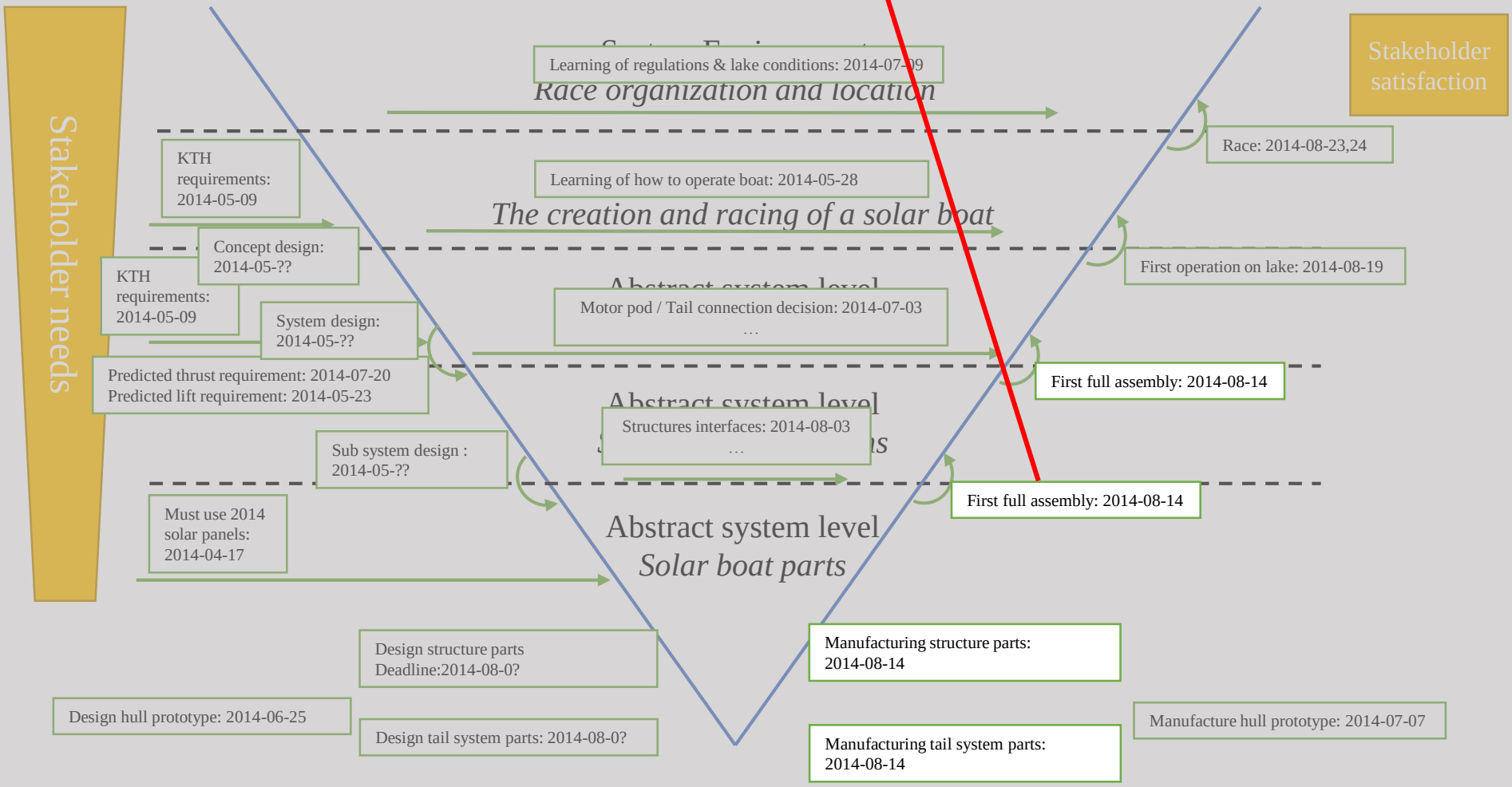
Development V: SolarBoat 2014

Unknown when design work products were complete and in what form they took

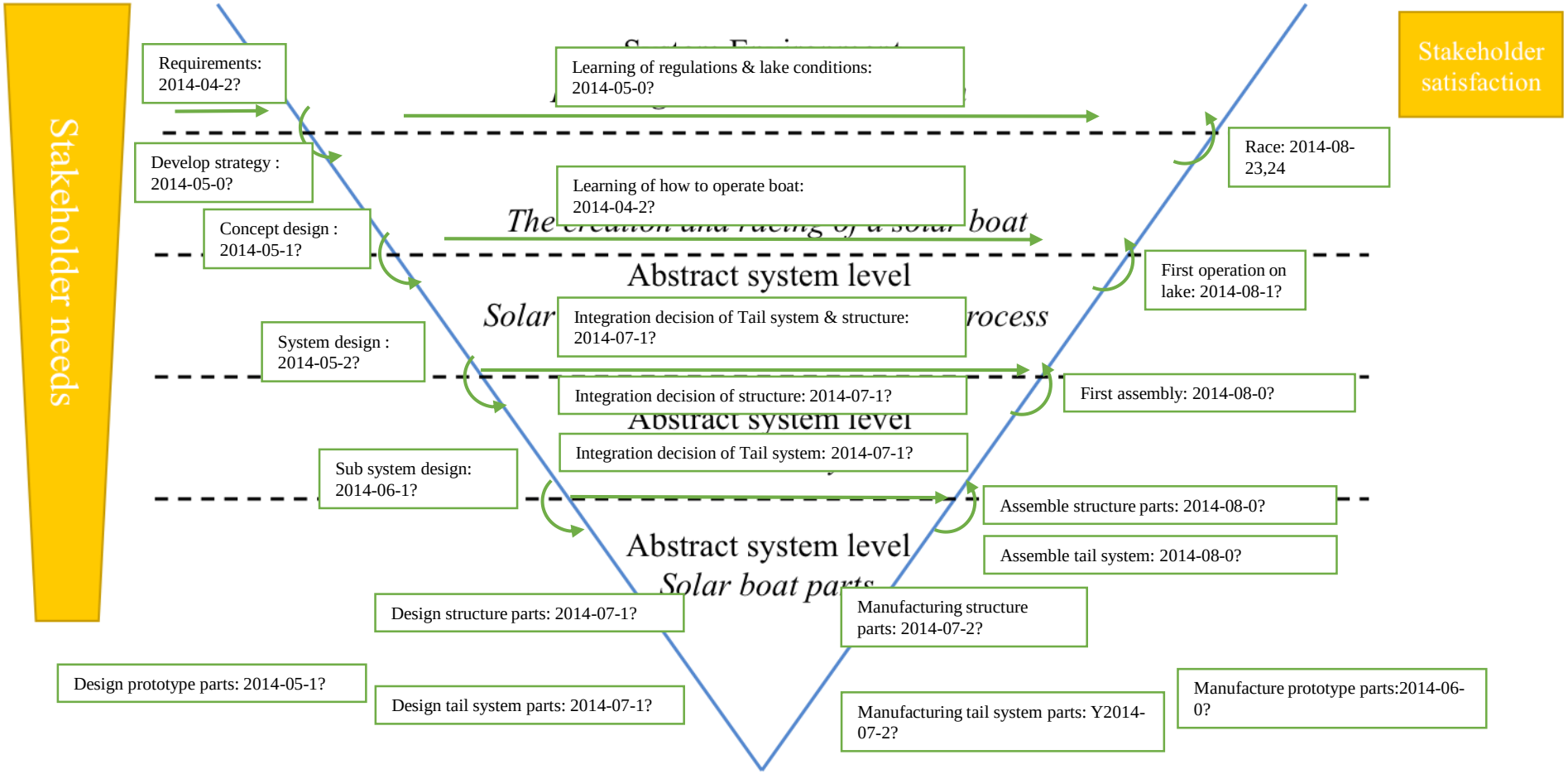


Development V: SolarBoat 2014

Manufacturing stopped and full systems integration occurred on the same day (on same day)

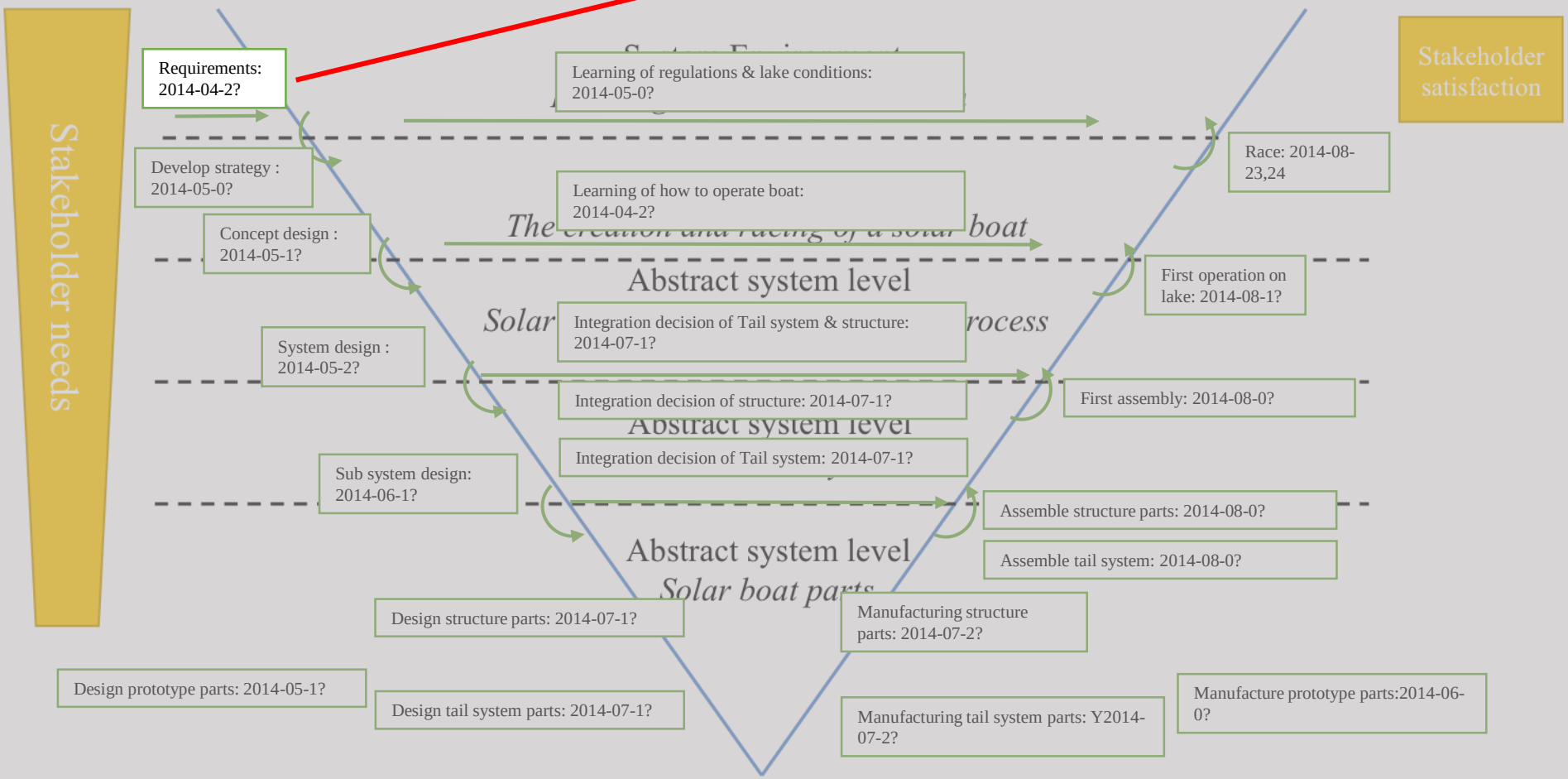


Development V: Alternative strategy



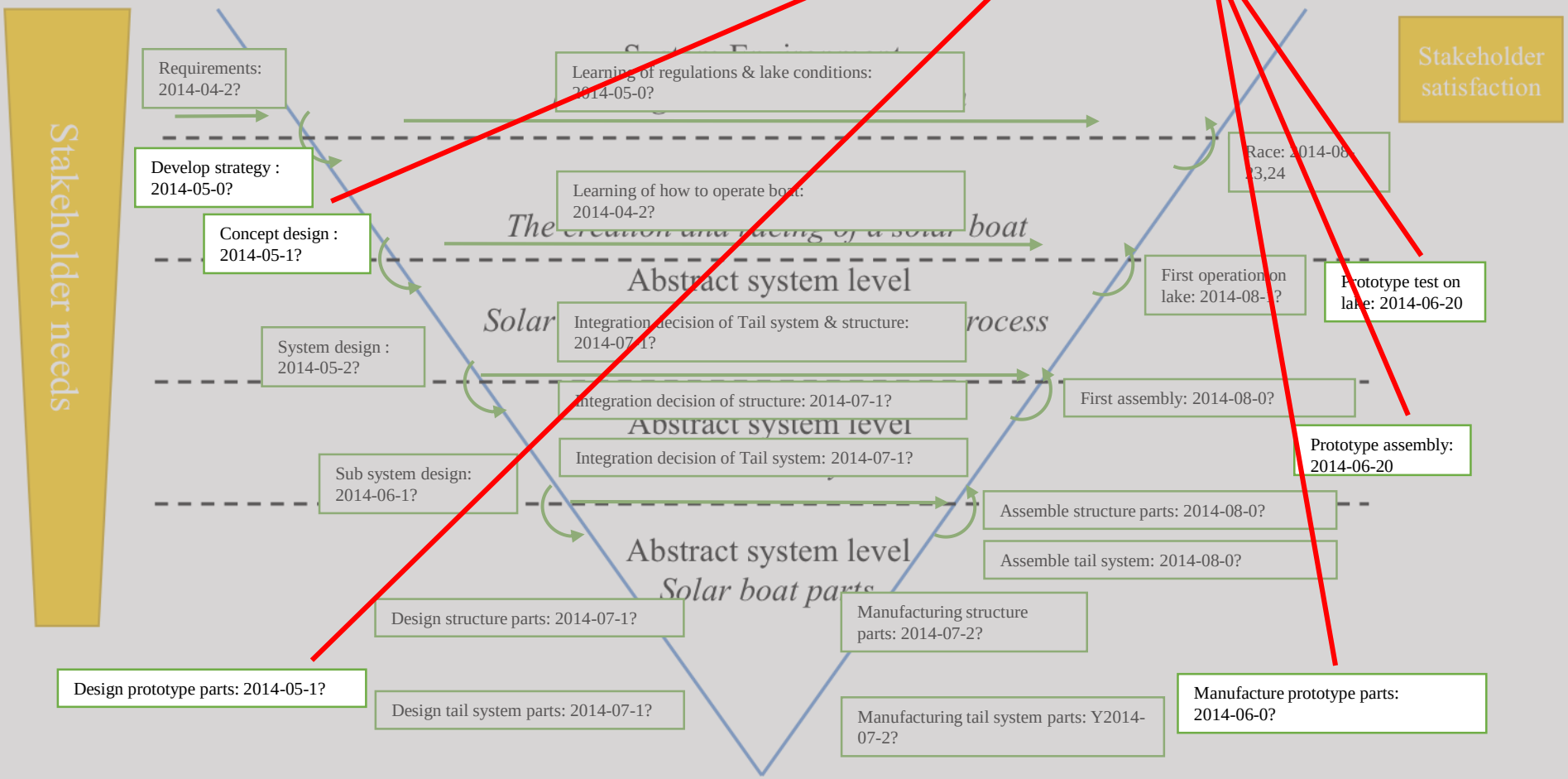
Development V: Alternative strategy

Simple requirements early based on high level goals



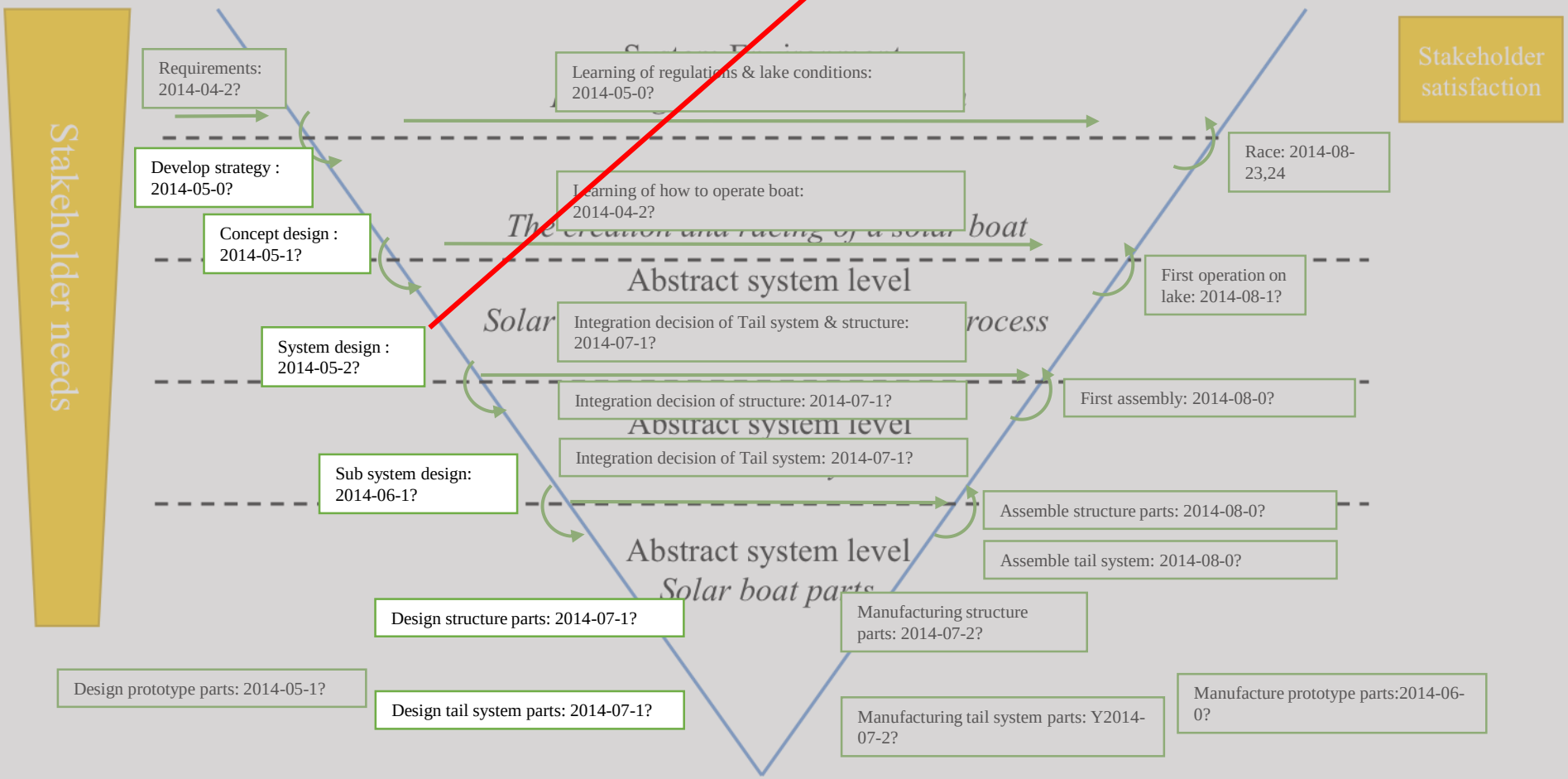
Development V: Alternative strategy

Develop strategy, concept and quickly develop and integrate a prototype

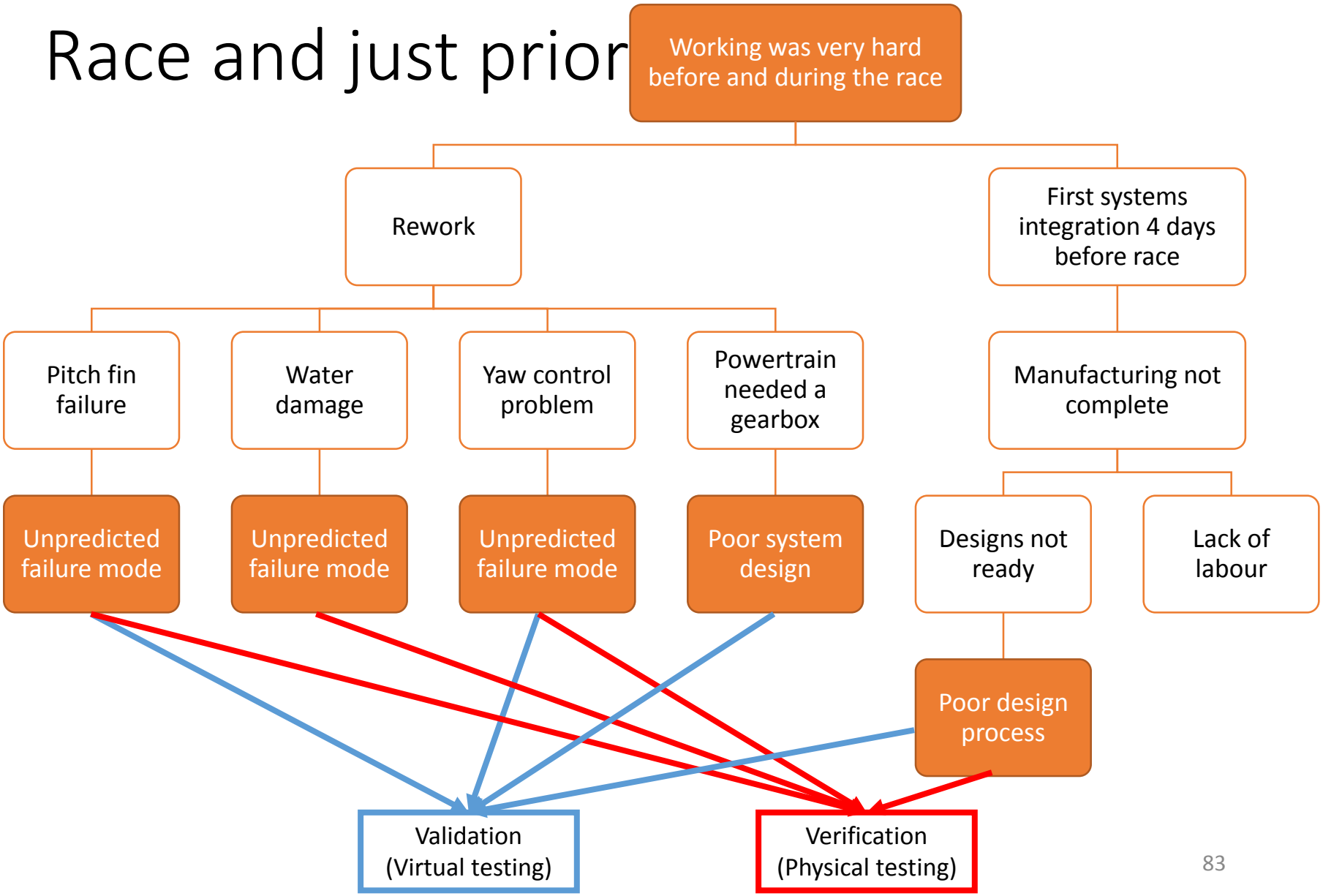


Development V: Alternative strategy

Define work products which define the system



Reflection on SolarBoat 2014: Race and just prior



Reflection on SolarBoat 2014: Design period