Multi-Dimensional Categorization of Research Software (@ deRSE)

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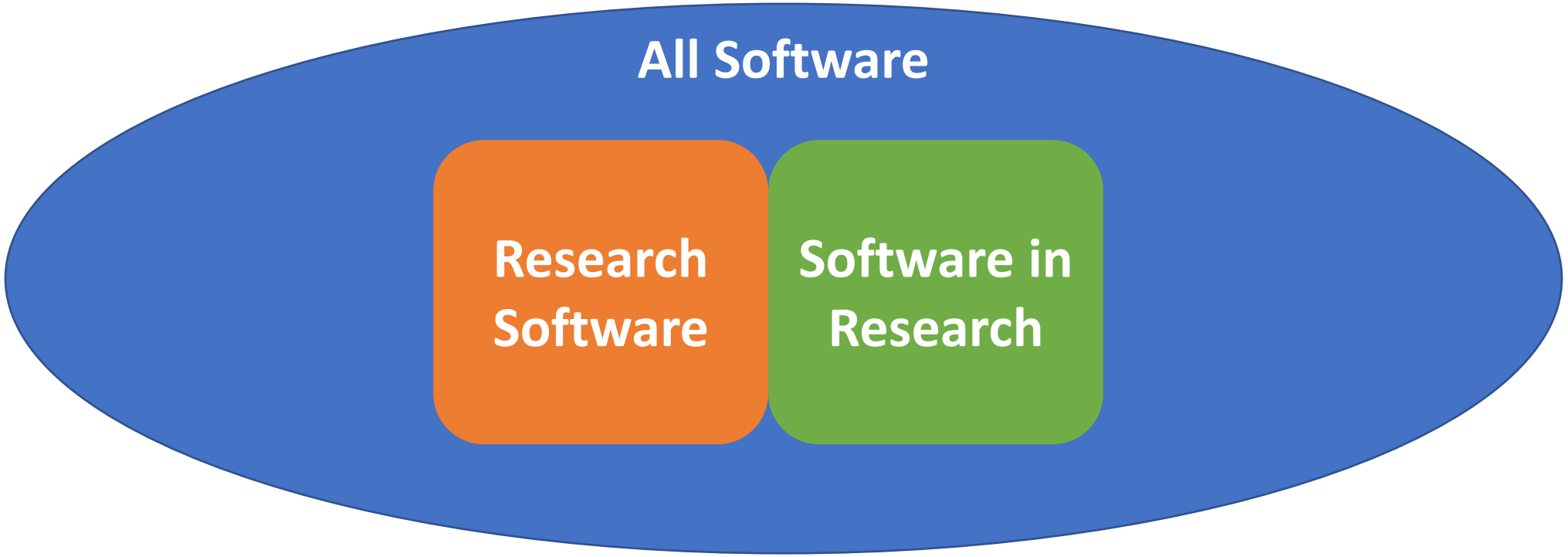
Research Software

RDA FAIR for Research Software (FAIR4RS) WG [Chue Hong et al. 2022] :

- **Research software** includes source code files, algorithms, scripts, computational workflows, and executables that are created **during** the research process or **for** a research purpose.
- Software components (e.g., operating systems, programming languages, libraries, etc.) that are used for research but were not created during or with a clear research intent should be considered `**software in research**´ and not `research software´.

Research software should be **FAIR** [Hasselbring et al. 2020b, Lamprecht et al. 2020] and **open** [Hasselbring et al. 2020a].

Software Segmentation



[Chue Hong et al. 2022]

Research Software
created during the research process or for a research purpose
Software in Research
used for research but not created during or with research intent

Context: German Special Interest Group GI-Fachgruppe “Research Software Engineering”

Interdisciplinary forum for:

- Software Engineering Researchers
- Research Software Engineers

https://fg-rse.gi.de/ (German)

Task Forces (Arbeitskreise):

- Categories of Research Software
- RSE Advocacy Strategy
- RSE Community Events
- RSE Online Community
- RSE Research
- RSE Software Development Guidelines
- RSE State of Nation Report

Multi-Dimensional Categorization of Research Software with Examples

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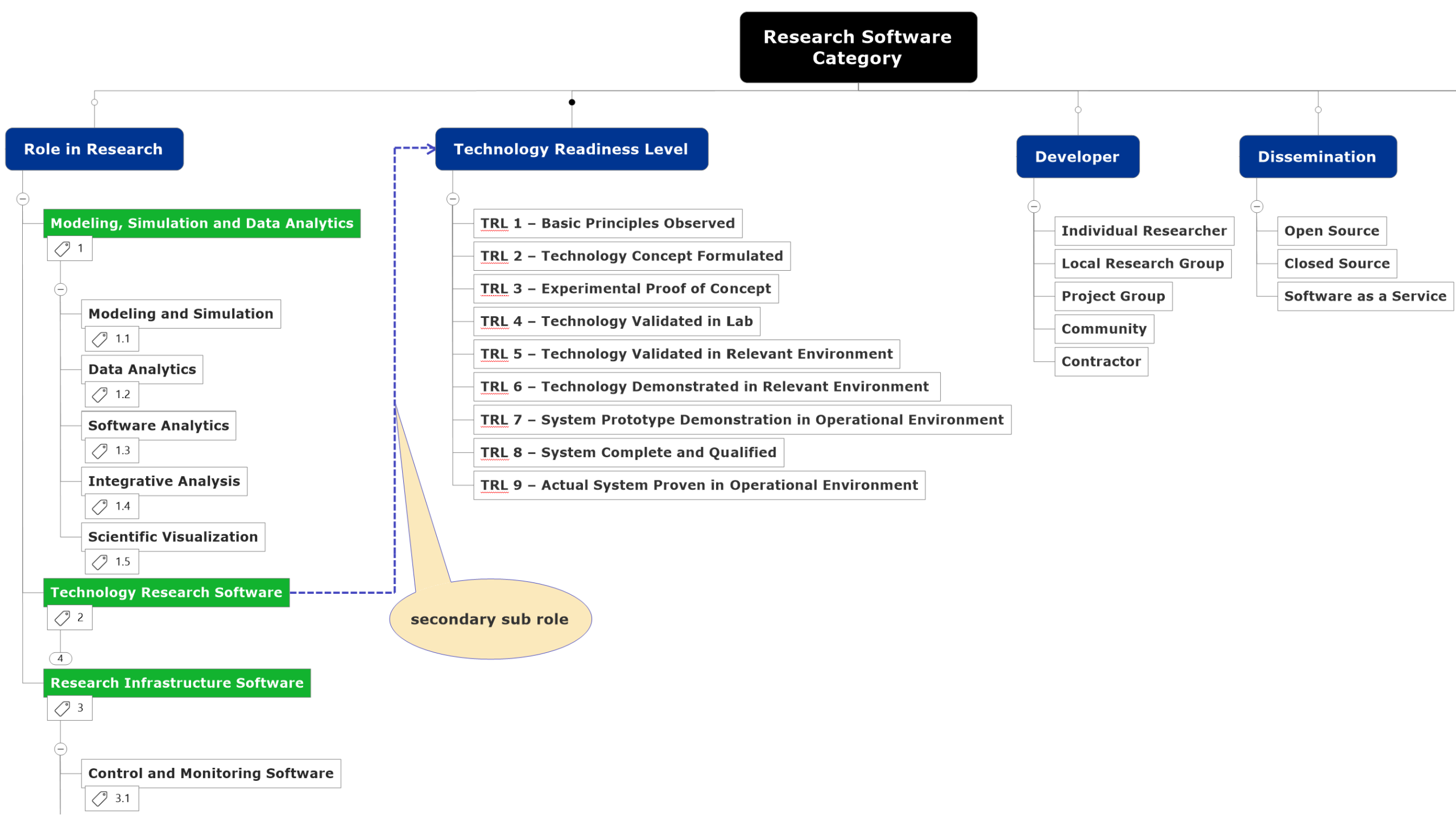
[Hasselbring et al. 2024]


Research Software Category
Role in Research
Technology Readiness Level
Developer
Dissemination
Modeling, Simulation and Data Analytics
1
Modeling and Simulation
1.1
Data Analytics
1.2
Software Analytics
1.3
Integrative Analysis
1.4
Scientific Visualization
1.5
Technology Research Software
2
4
Research Infrastructure Software
3
Control and Monitoring Software
3.1
TRL 1 – Basic Principles Observed
TRL 2 – Technology Concept Formulated
TRL 3 – Experimental Proof of Concept
TRL 4 – Technology Validated in Lab
TRL 5 – Technology Validated in Relevant Environment
TRL 6 – Technology Demonstrated in Relevant Environment
TRL 7 – System Prototype Demonstration in Operational Environment
TRL 8 – System Complete and Qualified
TRL 9 – Actual System Proven in Operational Environment
secondary sub role
Individual Researcher
Local Research Group
Project Group
Community
Contractor
Open Source
Closed Source
Software as a Service

Roles of Research Software

Research software's roles mainly fall into one of the following top-level role categories (and sometimes combinations):

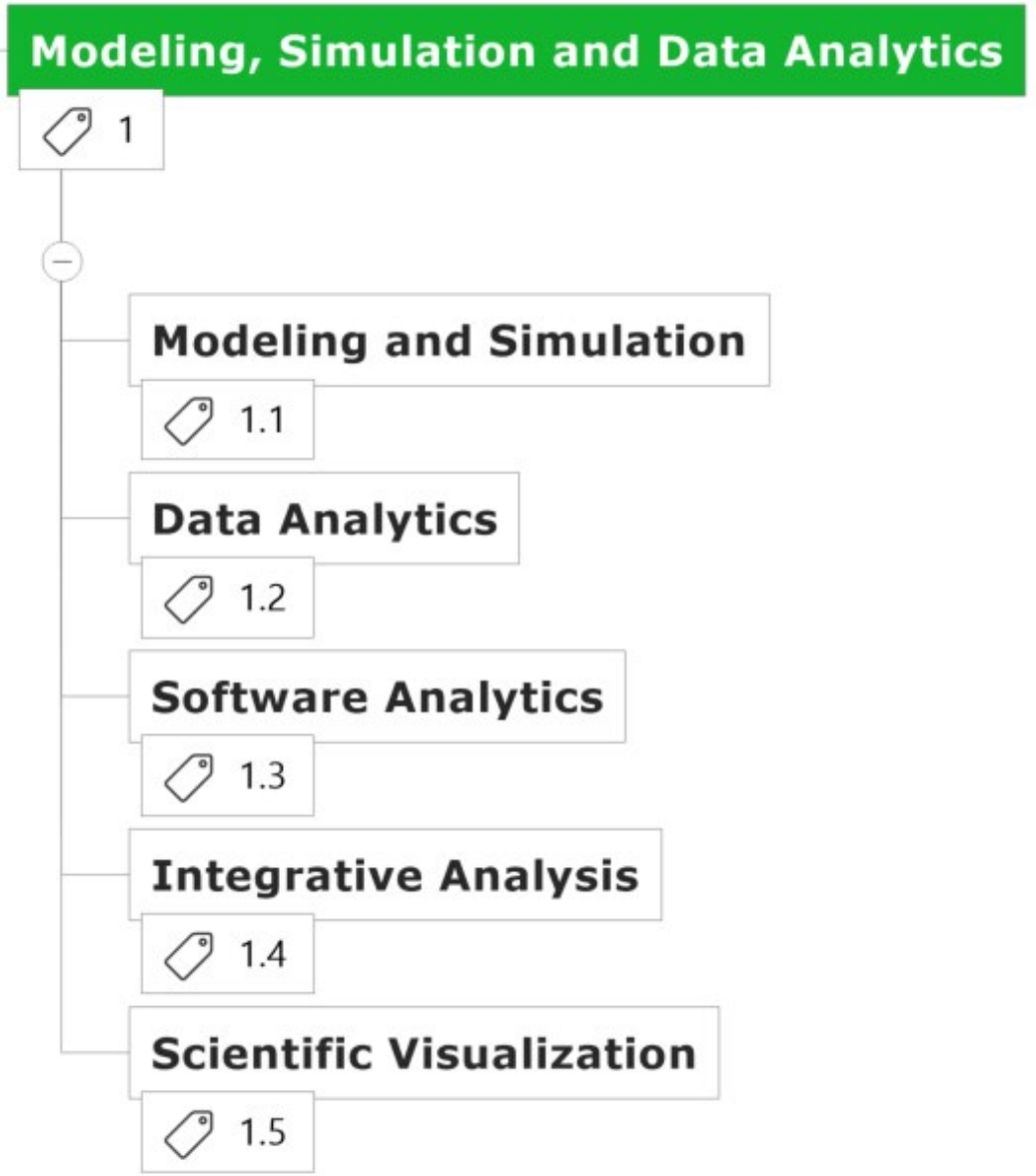
1. Modeling, Simulation and Data Analytics
2. Technology Research Software
3. Research Infrastructure Software

Let's take a look at the sub-categories via the mindmap.

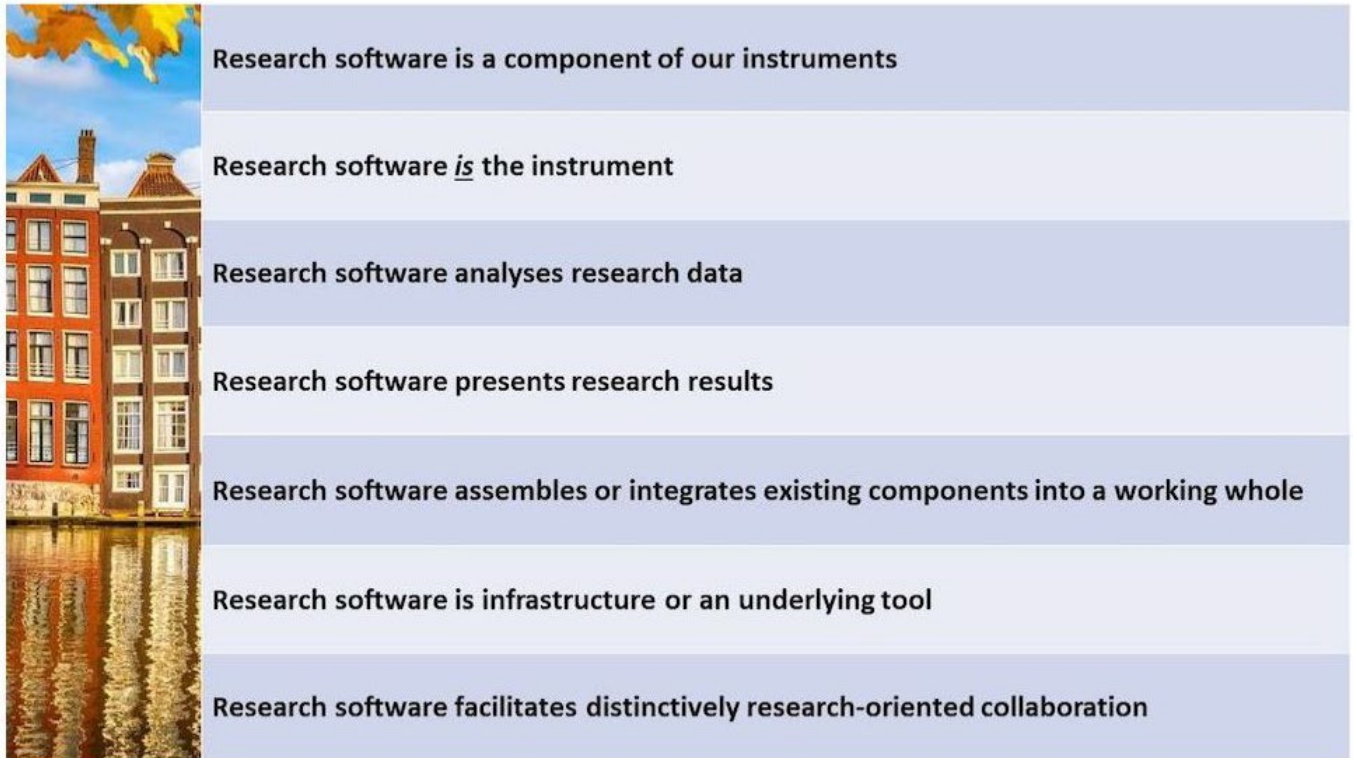
Refinement of Category 1

Modeling, Simulation and Data Analytics of, e.g., physical, chemical, social, or biological processes.

- **1.1 Modeling and Simulation** (e.g., numerical modeling, agent-based modeling)
- **1.2 Data Analytics**, on observation and simulation data, with statistical analysis and machine learning as methods
- **1.3 Software Analytics** (static, dynamic, evolution, repository mining)
- **1.4 Integrative Analysis** (data assimilation, decision analysis)
- **1.5 Scientific Visualization**



Related:
Defining the roles of research software
[van Nieuwpoort 2022, van Nieuwpoort and Katz 2023]



Category 3.1

Category 1 & 3

Category 1.2

Category 1.5

Category 3.3

Category 3

Category 3.6 – 3.8

Category 2 not included.

Update:
[van Nieuwpoort and Katz 2024]

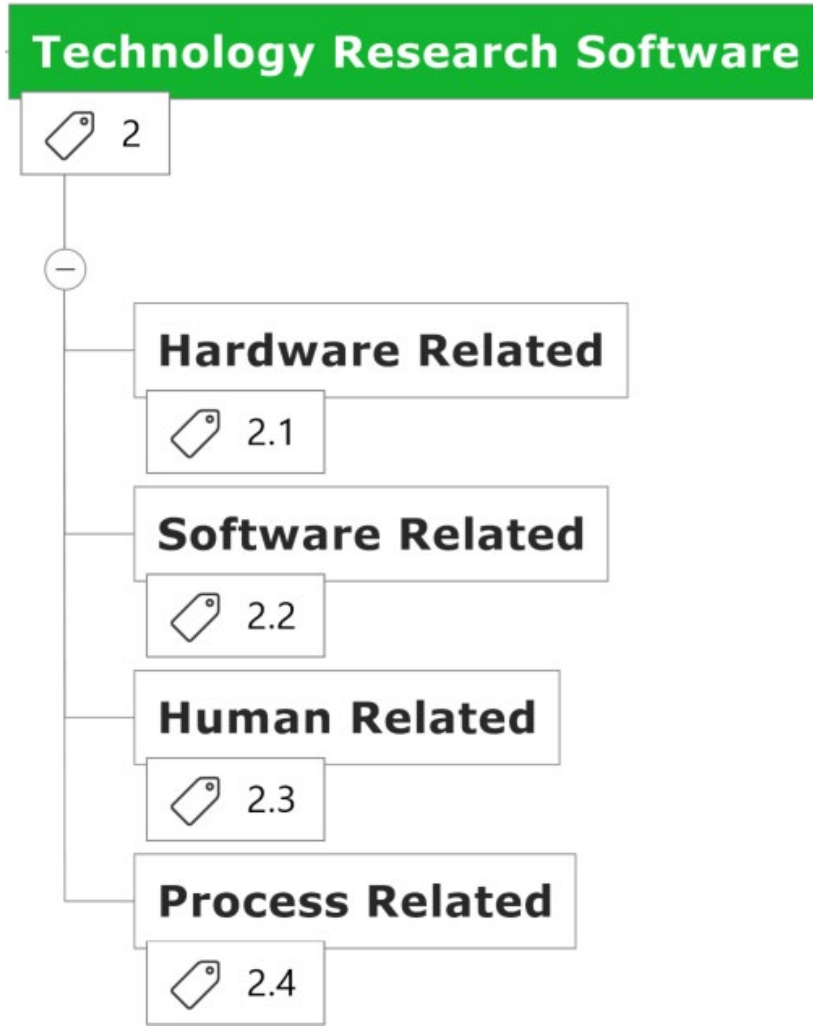
Research software is a component of our instruments
Research software *is* the instrument
Research software analyses research data
Research software presents research results
Research software assembles or integrates existing components into a working whole
Research software is infrastructure or an underlying tool
Research software facilitates distinctively research-oriented collaboration
Research software *itself* is a research tool for technology research

- In **technology research** (most often in computer science, and also in other disciplines), research software often plays a special role.
- Here, the research software **itself** is a key research tool
- For example, it can be a software **prototype** that **demonstrates** or explores a novel technological concept.
- An example is a computer science researcher who is researching **compiler technology**, with the idea of examining the performance of different options in programming language design.
- In this case, the **prototype compiler** is research software, since it is an artifact produced by computer science research. We therefore call this class of software “technology research software”.

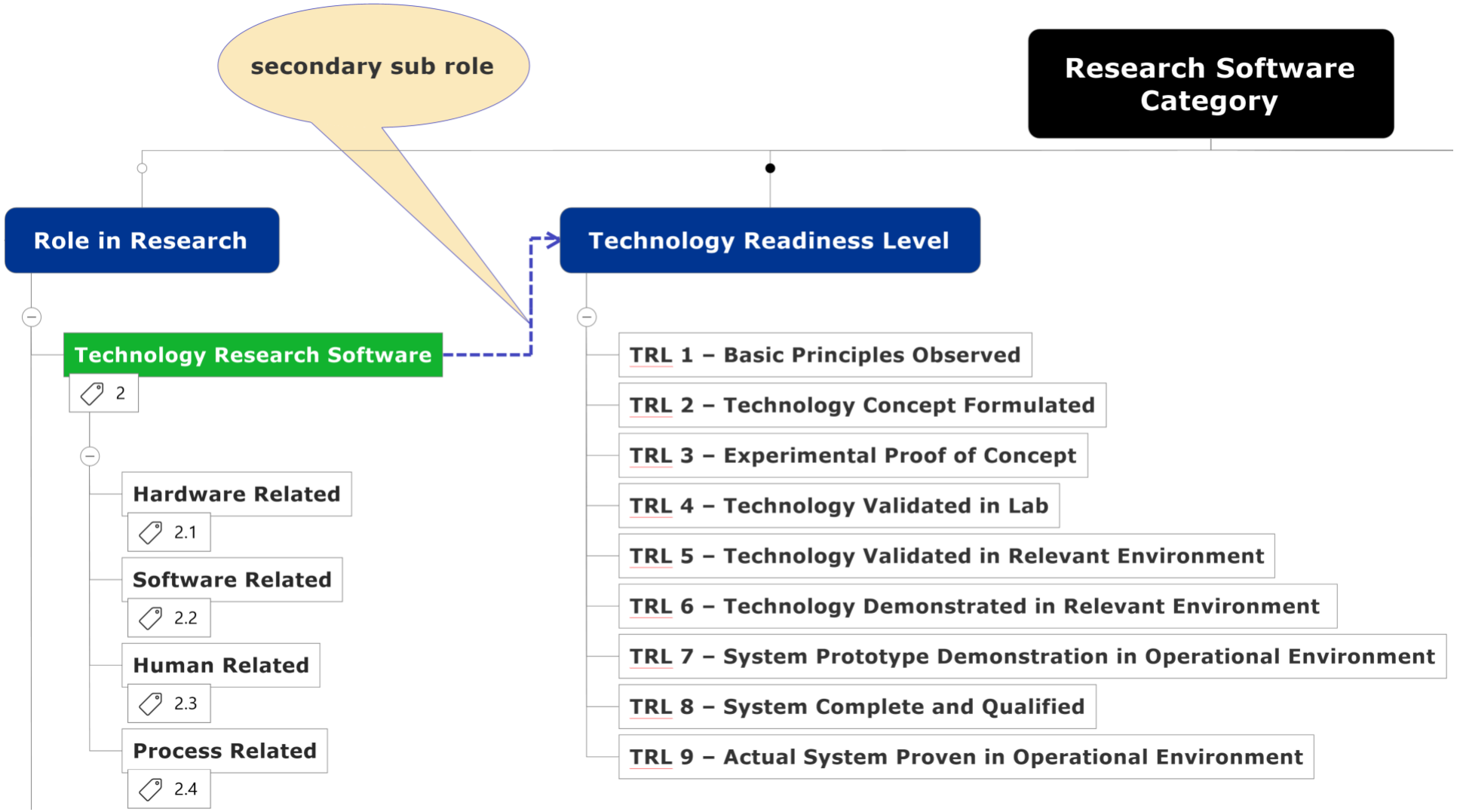
Refinement of Category 2

Technology Research Software in science and engineering research may be related to target contexts:

- **2.1 Hardware Related** (usually as embedded software)
- **2.2 Software Related** (e.g., as part of an operating system)
- **2.3 Human Related** (with a user interface)
- **2.4 Process Related** (e.g., as part of a business, development or production processes)



Technology Readiness Levels as Secondary Sub Roles



Category 3: Research Infrastructure Software

3.1 Control and Monitoring Software for complex experiments and instruments. This includes embedded control software, as well as native and web-based monitoring software

3.2 Data Collection and Generation (survey software, sensor-based data collection, synthetic data generation, etc.)

3.3 Pipelines and Tools

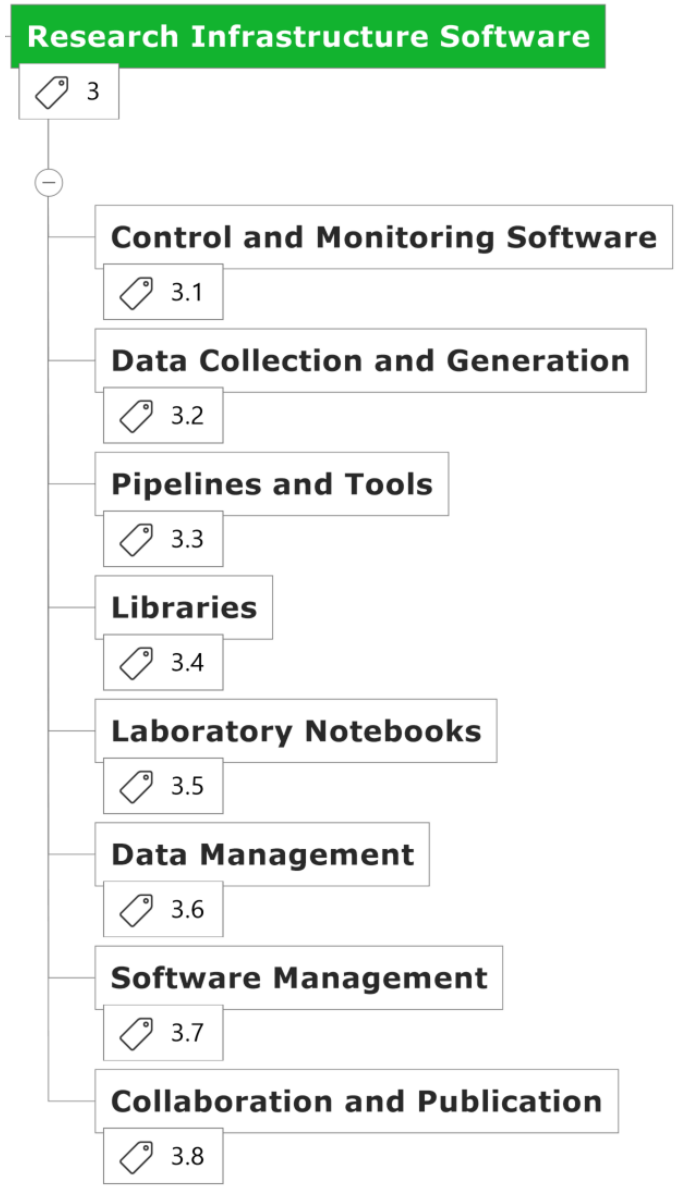
3.4 Libraries, for instance for high performance computing

3.5 Laboratory Notebooks

3.6 Data Management

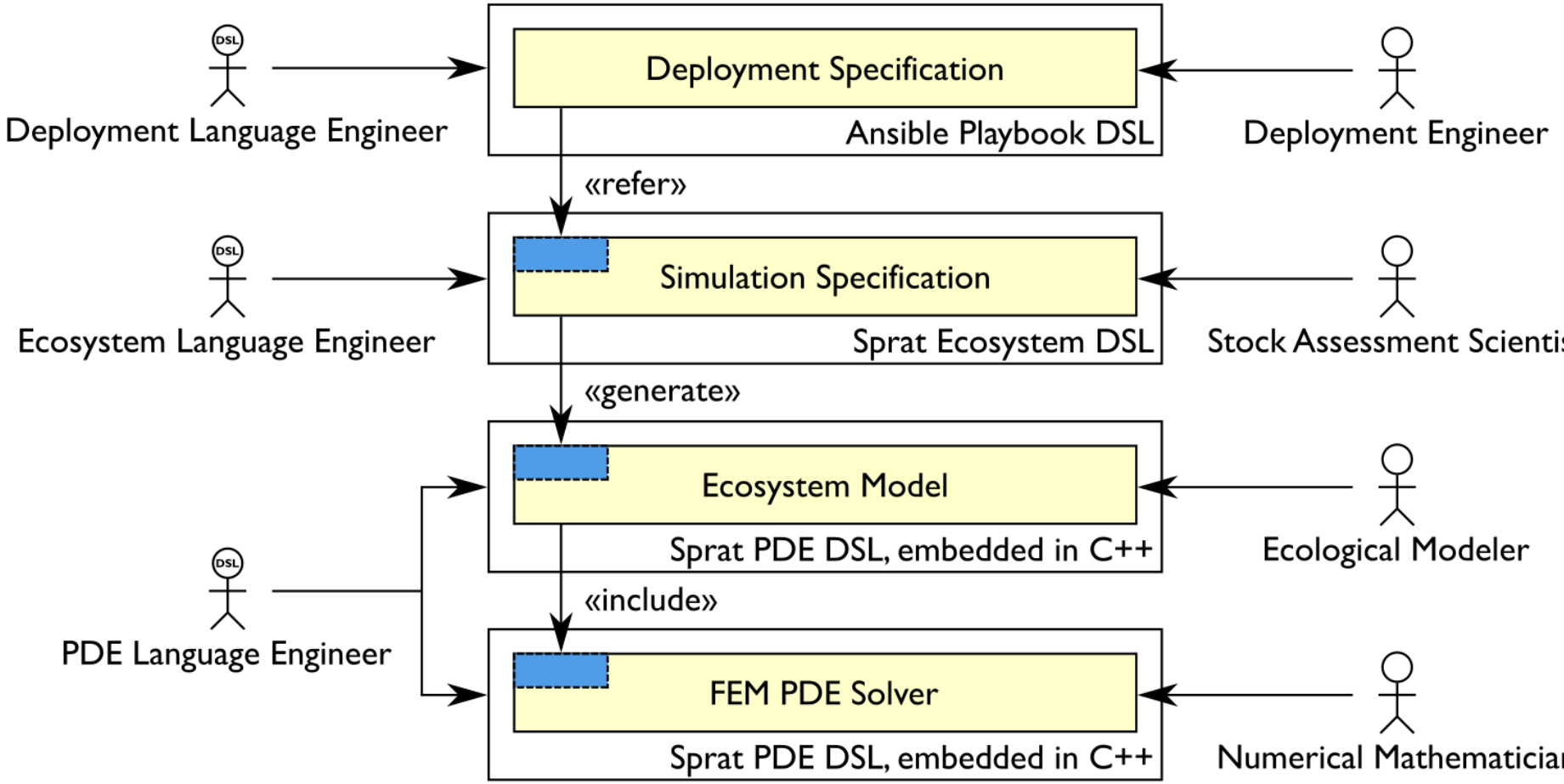
3.7 Software Management

3.8 Collaboration and Publication



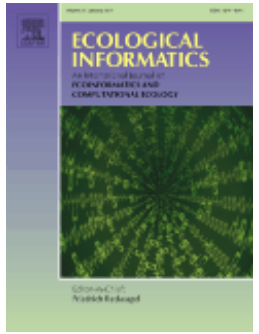
Multi-Dimensional Categorization of Research Software Examples

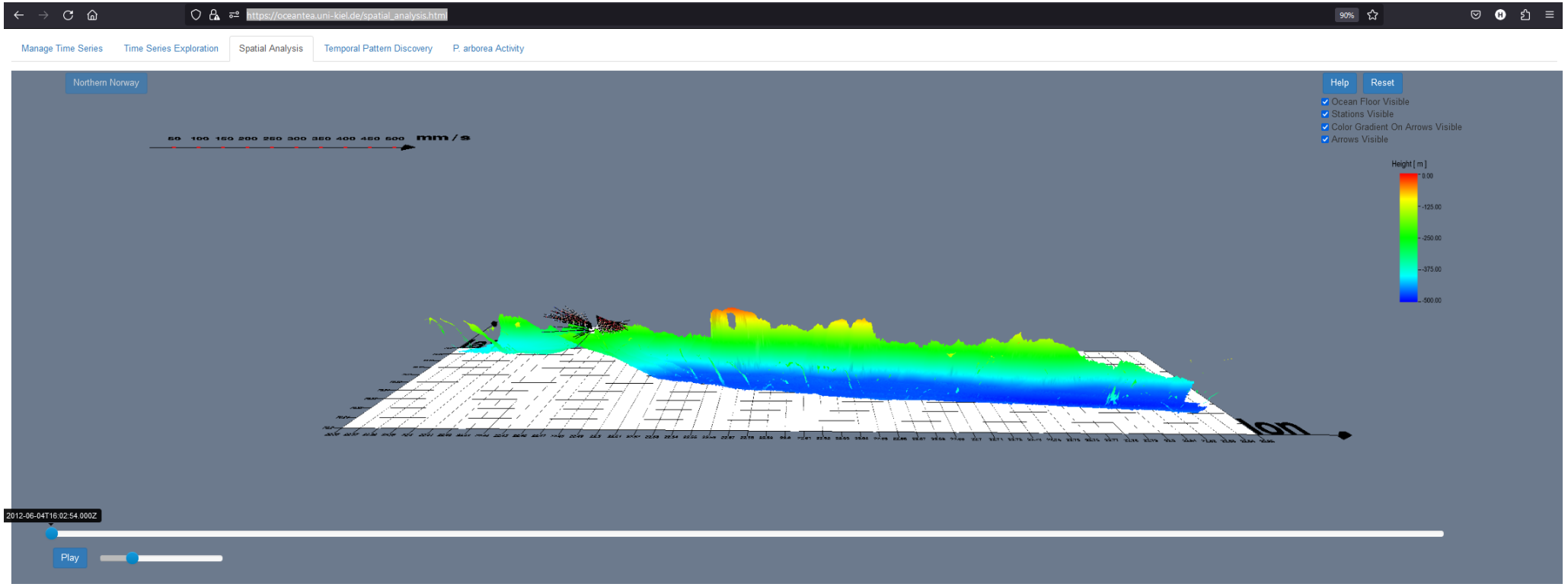
Example for Category 1.1 (Modeling and Simulation): The Sprat Marine Ecosystem Modeling Languages



[Johanson & Hasselbring 2014a,b, 2016b, Johanson et al. 2017a, Johanson & Hasselbring 2017]

Example for Category 1.2 (Data Analytics): OceanTEA: Analyzing Ocean Observation Data





Paper on the analysis results: [Johanson et al. 2017b]
Paper on the software architecture: [Johanson et al. 2016a]
Code: https://github.com/cau-se/oceantea

future ocean
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Role	Readiness	Developer	Dissemination
1.1 Modeling and Simulation 1.5 Scientific Visualization	TRL 5 [84]	Individual Researcher	Open Source

TABLE 13. Multi-dimensional categorization of the **SPRAT** marine ecosystem model simulation approach [85].

Role	Readiness	Developer	Dissemination
1.2 Data Analytics 1.5 Scientific Visualization	TRL 4 [67]	Local Research Group	Open Source Software as a Service

TABLE 10. Multi-dimensional categorization of the **OceanTEA** ocean observation data analytics tool [68].

[Hasselbring et al. 2024]

Examples for Category 2 (Technology Research Software)

https://github.com/kieker-monitoring

Kieker: A monitoring framework for software engineering research
[van Hoorn et al. 2012, Hasselbring and van Hoorn 2020]

https://github.com/ExplorViz

ExplorViz: Research on software visualization, comprehension and collaboration
[Hasselbring et al. 2020c]

https://www.theodolite.rocks

The Theodolite Scalability Benchmarking Framework
[Henning and Hasselbring 2021, 2022, 2024]

Multi-dimensional categorization of the **Kieker** observability and monitoring framework:

Role	Readiness	Developer	Dissemination
1.3 Software Analytics 2.2 Software Related	TRL 4 [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53] TRL 5 [54] TRL 6 [55]	Community SustainKieker Gefördert durch DFG Deutsche Forschungsgemeinschaft	Open Source

Multi-dimensional categorization of the **ExplorViz** software visualization tool:

Role	Readiness	Developer	Dissemination
1.3 Software Analytics 1.5 Scientific Visualization 2.2 Software Related	TRL 4 [31], [32], [33], [34], [35], [36] TRL 5 [37]	Local Research Group	Open Source Software as a Service [38]

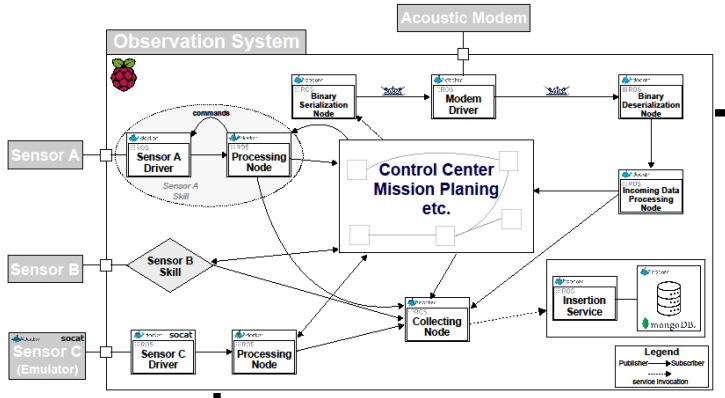
Multi-dimensional categorization of the **Theodolite** benchmarking framework:

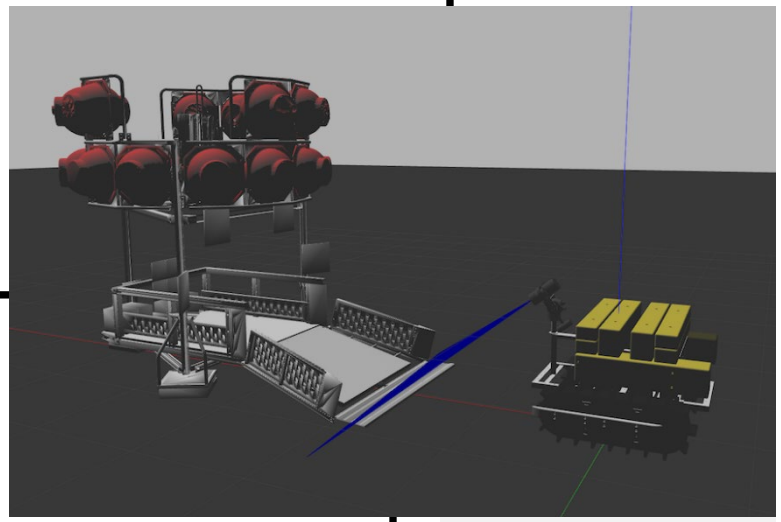
Role	Readiness	Developer	Dissemination
2.2 Software Related 3.3 Pipelines and Tools	TRL 4 [86] TRL 5 [87], [88]	Project Group	Open Source

[Hasselbring et al. 2024]

Example for Category 3.1 (Control & Monitoring): Software for Ocean Observation Robotics

Digital Twin Prototype





Digital Twin

Physical Twin

[Barbie et al. 2021]

GEOMAR

Multi-Dimensional Categorization of the ARCHES Digital Twin Framework

Role	Readiness	Developer	Dissemination
2.1 Hardware Related 3.1 Control and Monitoring Software	TRL 4 [25] TRL 5 [26] TRL 7 [24]	Project Group	Open Source

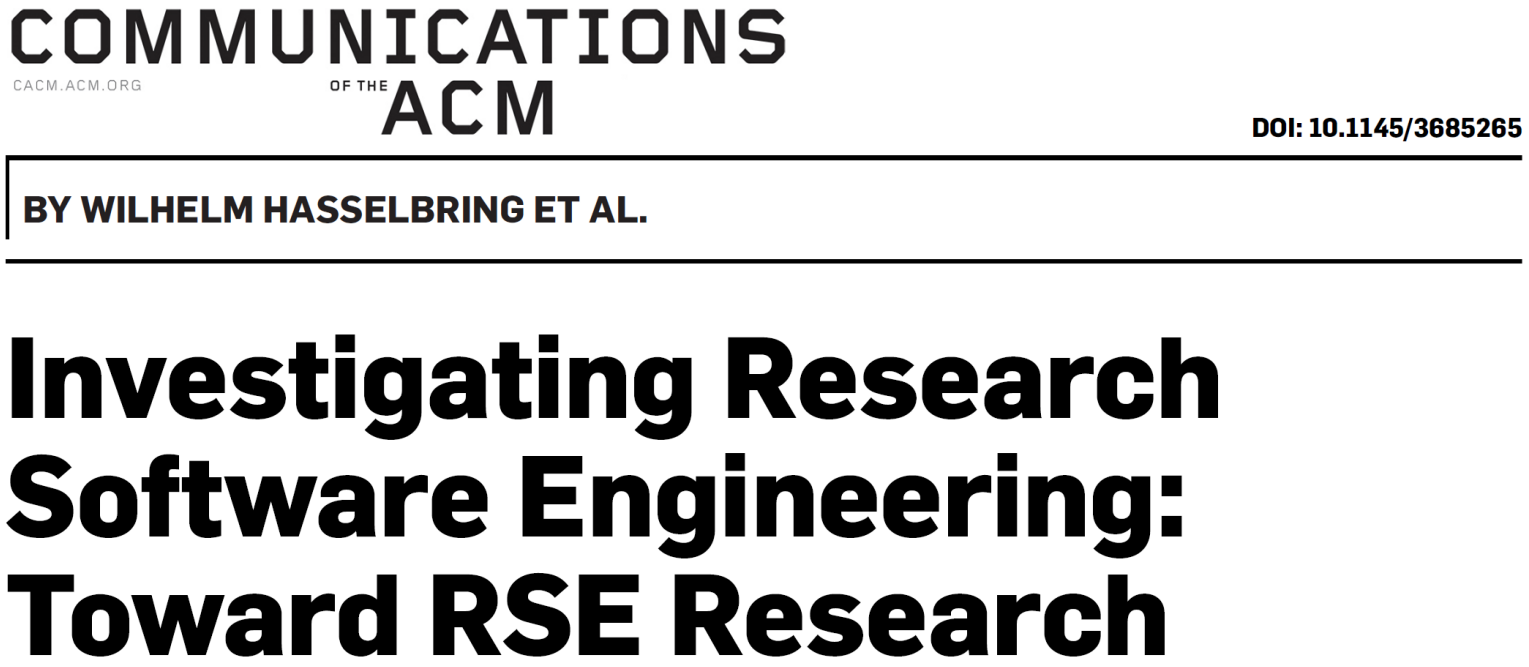
[Hasselbring et al. 2024]

https://irser.github.io/

Outlook:
Research Software Engineering Research

Research Software Engineering

Software Engineering Research



https://player.vimeo.com/video/1045834267 [Felderer et al. 2025].

Categorization for RSE Research

- In the realm of RSE research, we hope that the categorization provides a framework for classifying research objects, supporting software corpus analyses, and enhancing our understanding of the different types of research software and their properties.
- This structured approach may aid in organizing and interpreting the vast landscape of research software, contributing to advancements in RSE methodologies and practices.
- As selected dimensions, we presented our proposed role-based, readiness-based, developer-based, and dissemination-based categories.

Slides

https://oceanrep.geomar.de/id/eprint/61725/

Backup Slides

Purpose of Research Software Categories

Categories for research software may serve

- as a basis of **institutional guidelines** and checklists for research software development;
  - to better understand the different types of research software and their specific **quality** requirements;
  - to recommend appropriate software engineering **methods** for the individual categories;
- to design appropriate **teaching / education** programs for the individual categories;
- for a better assessment of existing software when deciding to **reuse** it;
- for research funding agencies, to define appropriate **funding** schemes;
- to define appropriate **metadata** labels for FAIR research software;
- in RSE Research, to provide a framework for classifying **research software artifacts**.

This list is not exhaustive.

Characterization of Categorizations

Criterion	Explanation
Scope	This categorization covers the dimensions of roles, readiness, developers, and dissemination.
Purpose	The categorization aims to enable a better understanding of the different types of research software and their specific quality requirements.
Context	The categorization has been produced in the context of a task force of the special interest group on Research Software Engineering, within the German Association of Computer Science (GI e.V.) and the German Society for Research Software (de-RSE e.V.). It is meant to serve different purposes, in particular RSE research [7], [8].
Properties	The categories follow different relevant dimensions, and are defined collaboratively among software engineering researchers and research software engineers.
Consequences for Creation	Depending on its category, software is expected to meet different quality requirements and follow different development processes.
Consequences for Use	Perceive that there are many different types of research software, fulfilling many different roles and functions.
Inter-categorial relations	Individual research software may change its category within one or more dimensions.

TABLE 2. Characteristics of our multi-dimensional categorization for research software.

[Hasselbring et al. 2024]

Category 2:
Technology Research Software

- "**Technology** is the application of conceptual knowledge for achieving practical goals, especially in a reproducible way.
  - The word technology can also mean the products resulting from such efforts, including both tangible tools such as utensils or machines, and intangible ones such as **software**." https://en.wikipedia.org/wiki/Technology
- **Engineering Research** (AKA Design Science) is research that invents and evaluates **technological** artifacts.[1]
  - Could also be called Technology Research, see [van Nieuwpoort and Katz 2024].
- The refinement via "**Technology Readiness Levels**" should be appropriate [Rose et al. 2017].

[1] https://github.com/acmsigsoft/EmpiricalStandards/blob/master/docs/standards/EngineeringResearch.md

Technology Research Software Secondary Sub Roles

- The TRLs constitute sub roles of technology research software.
- One specific technology research software may take several such sub roles over its lifecyle, with increasing “readiness”.
- It may also take several roles at the same time, within different contexts:
  - In one project context, it may serve as “Experimental Proof of Concept” (TRL 3);
  - in another project, it may already serve as a “Technology Validated in Lab” (TRL 4).
  - Eventually, a technology research software may even become an “Actual System Proven in Operational Environment” (TRL 9).

“Modeling and Simulation Research Software” vs. “Technology Research Software”

The difference between the categories “Modeling and Simulation” and “Technology Research Software” (without consideration of the TRL sub roles) may be illustrated, for instance, with control engineering research:

- As a control engineering researcher, you may build a simulation of a control system.
- As a control engineering researcher, you may also build an actual control system as a new software system.
  - In an automation lab, this researcher may then experiment with this system (not with the simulation of the system).
  - If this system (which is a technology research software) matures, it may reach higher TRLs.

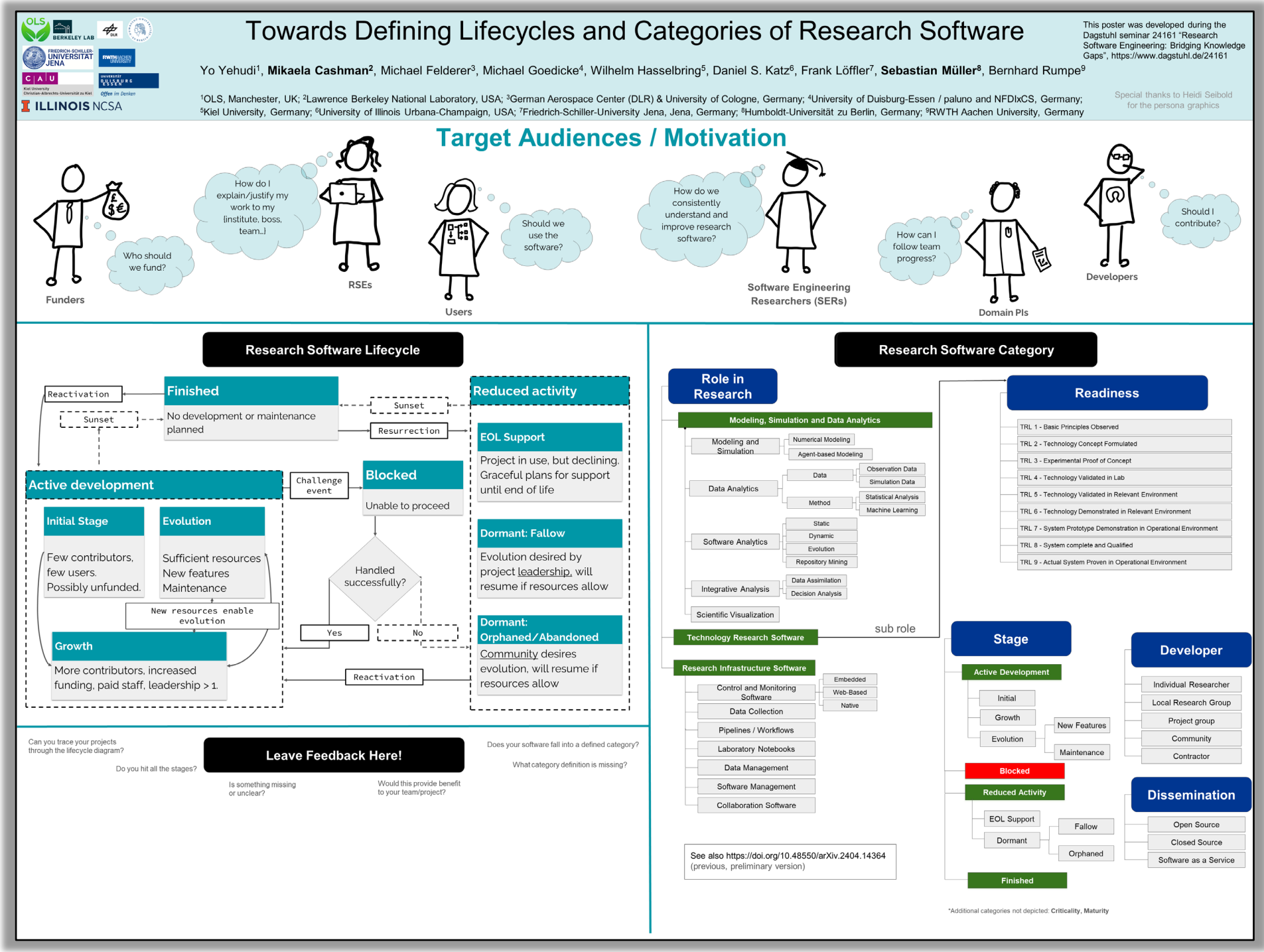
Here, both, the simulation and the actual control system are research software.

- The simulation software may even become part of the actual control system (for instance, for prediction), turning it into technology [research software].

Additional Dimension:

Lifecyle Stages

[Yehudi et al. 2024]



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