



# Model-Driven Design Decision Support Systems for Complex Engineering Systems

Challenges in Early-Design Stages

**Licentiate Candidate:**

Mubeen Ur Rehman

**Supervisors:**

Prof. Alessandro Bertoni, BTH, Sweden

Asst. Prof. Johan Wall, BTH Sweden

**Examiner:**

Prof. Tobias Larsson, BTH, Sweden

**Opponent:**

Dr. Mehdi Tarkian, Linköping University, Sweden

2025-09-17



**Department of  
Mechanical Engineering**

# Model-Driven Design Decision Support Systems for Complex Engineering Systems

## Challenges in Early-Design Stages

Mubeen Ur Rehman

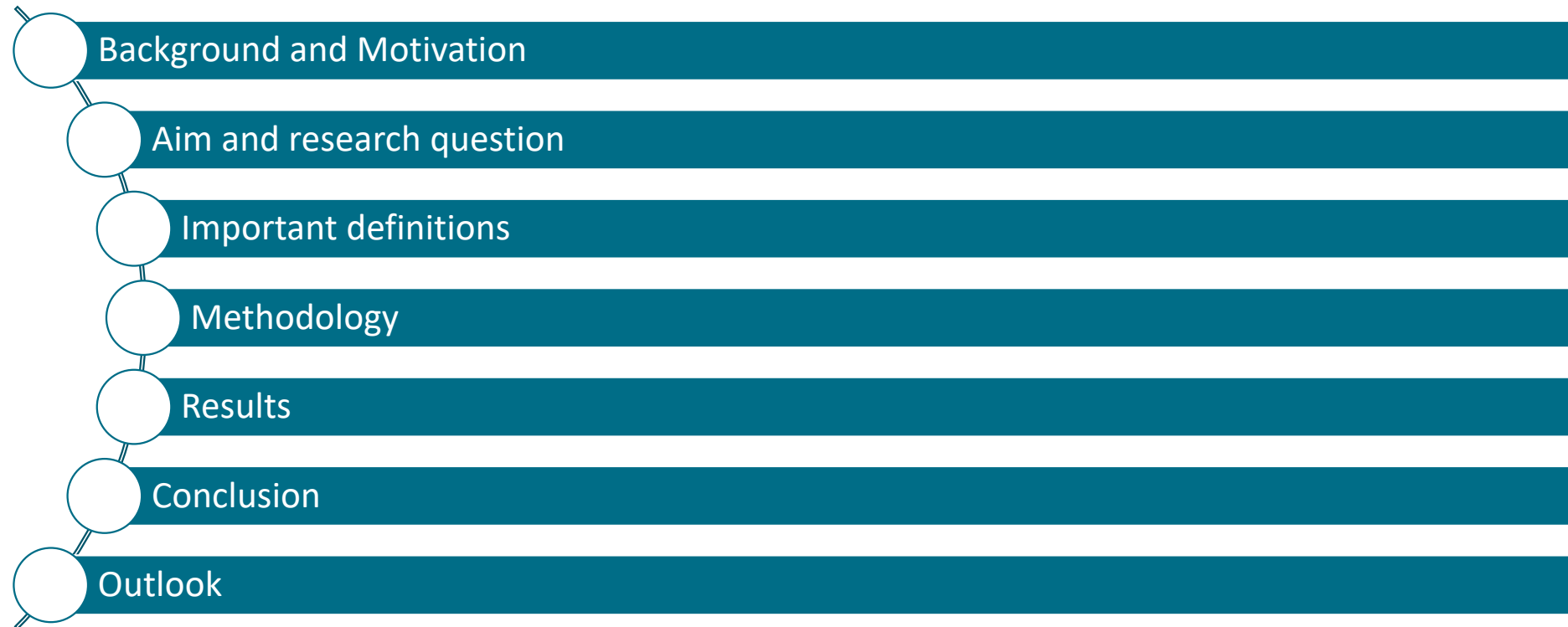
Blekinge Institute of Technology

2025-09-17



**Department of  
Mechanical Engineering**

# Agenda of the Presentation



# Impact of Early-stage decision

## Decision:

- Shift from aluminum to carbon-fiber composites.

## Consequence:

- Major weight reduction (~20%) and efficiency gains (~20%)
- Huge supply chain complexity and costly delays. (~3 years delay, \$6B Ballooned to \$32B)



Boeing Dreamliner. Handout/Getty Images

# Impact of Early-stage decision

## **Decision:**

- Utzon's unique sail-like roof design was approved before engineering feasibility was understood.

## **Consequence:**

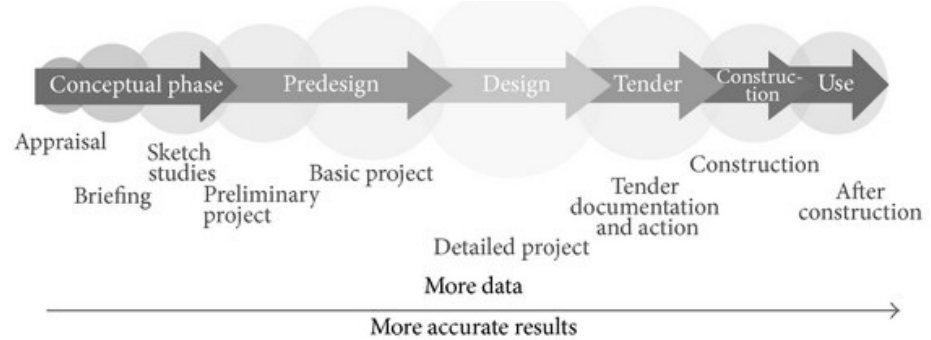
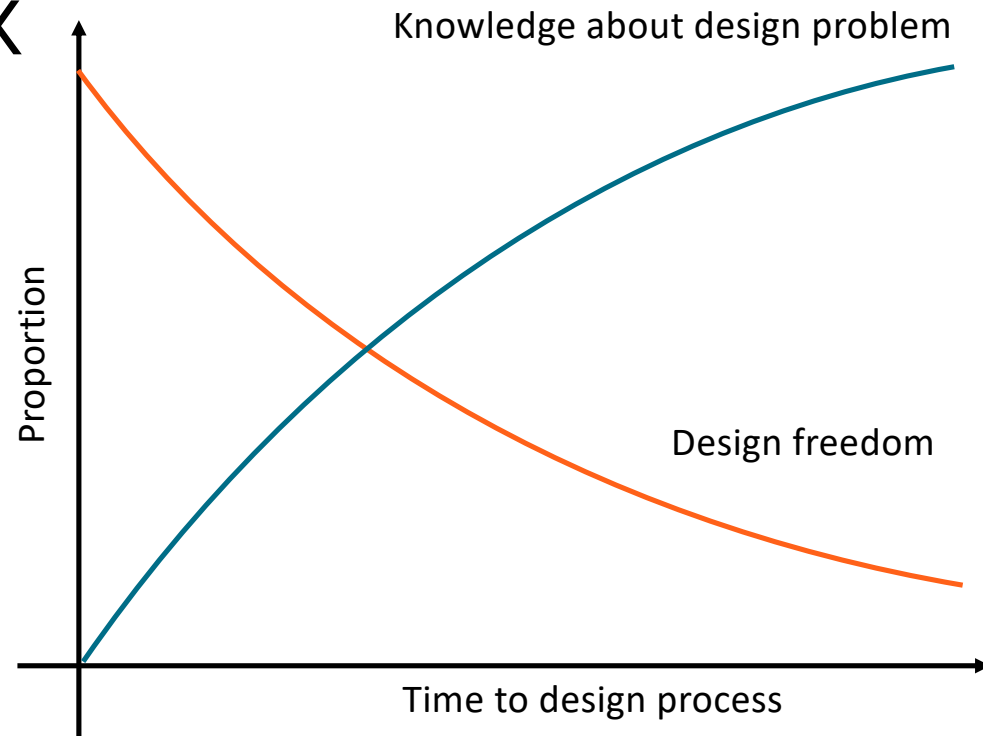
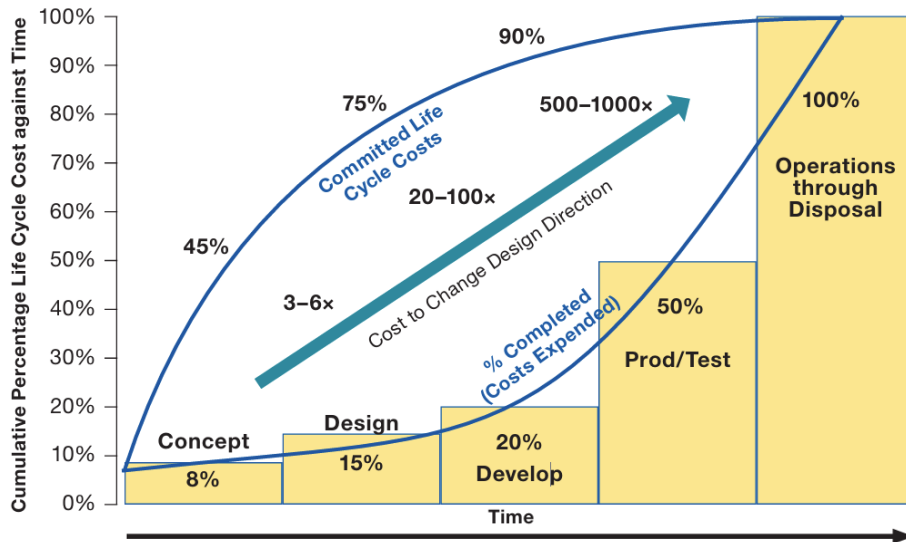
- Cost exploded from \$7M to \$102M, project delayed 10 years.



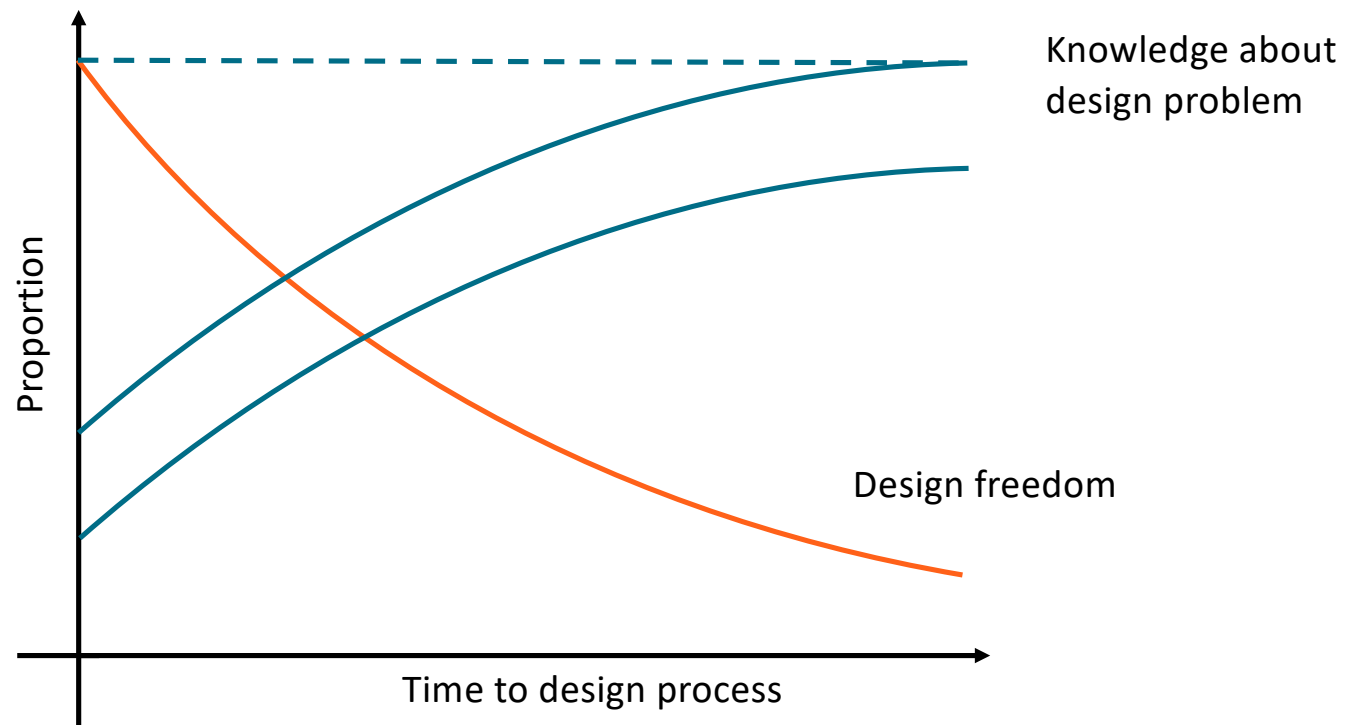
Photo: Getty Images

# The design Paradox

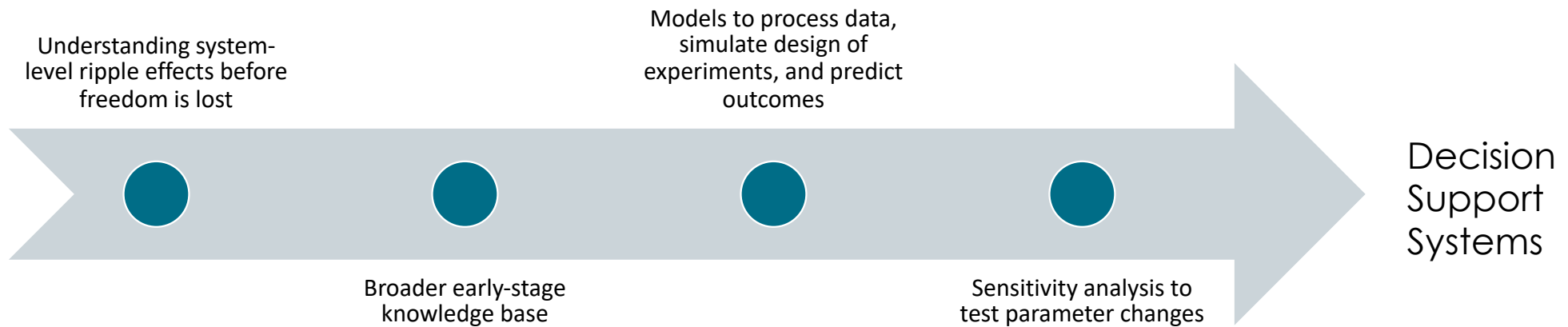
## Costs?



# A Better Scenario..

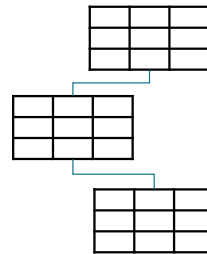
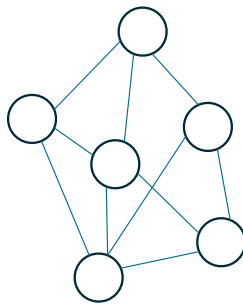
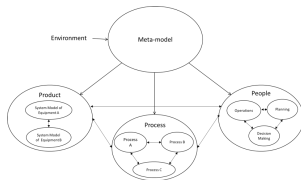
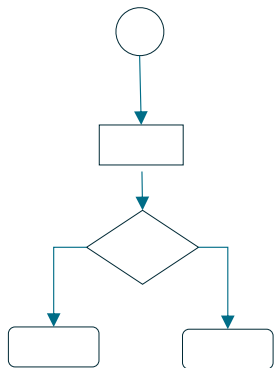


# How to have better Scenario?



Move from intuition-driven to evidence-supported decisions

# Decision Support System



# Aim and Research Question

To investigate **the challenges** encountered when using Model-Driven Design **Decision Support Systems** in **early-stage** design decision-making in **Complex Engineering Systems**

# Research Question

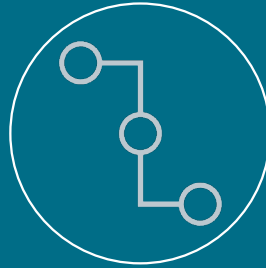
*RQ: What are the **key challenges** associated with current model-driven decision support systems used during early-stage design in complex engineering systems?*

# Important definitions

# Complex Engineering Systems



Heterogeneity



Interconnectivity



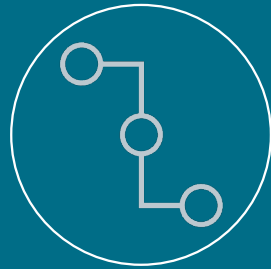
Emergence



# System of Systems



Heterogeneity



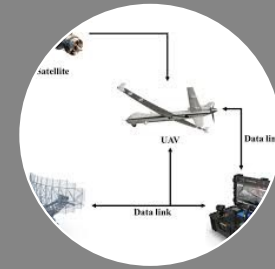
Interconnectivity



Emergence



Managerial  
Independence



Geographical  
Distributed



# Example (CES)



## Heterogeneity

- Different physical domains (mechanical, hydraulic, software, electrical) coexist.

## Interconnectivity

- Engine torque  $\leftrightarrow$  transmission efficiency  $\leftrightarrow$  fuel consumption
- A change in one subsystem cascades into others

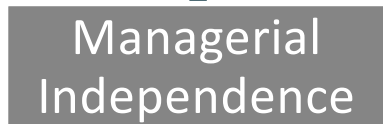
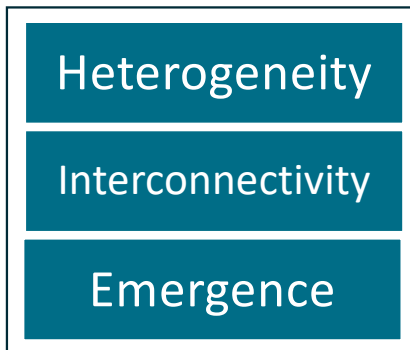
## Emergence

- Overall hauling **productivity**
- Fuel efficiency

<https://media.volvogroup.com/dam/spaces/33f026ad011b401988deb895fc0facfc/items/b6189240997e4e71847fb25f010d1e9f>

# Example (SoS)

Fleet of Construction Equipment in a Quarry



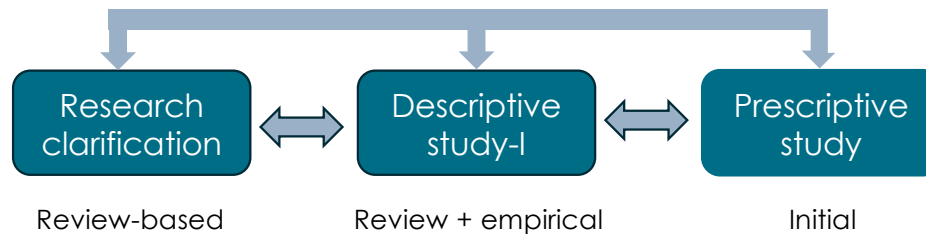
Taken from Volvo 'Overview of Electric Site'

# Methodology

# Research Methodology

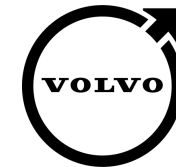
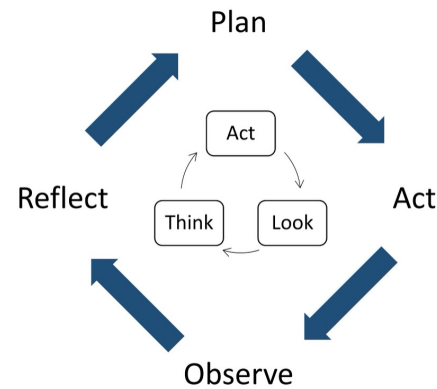
Method

Design Research  
Methodology

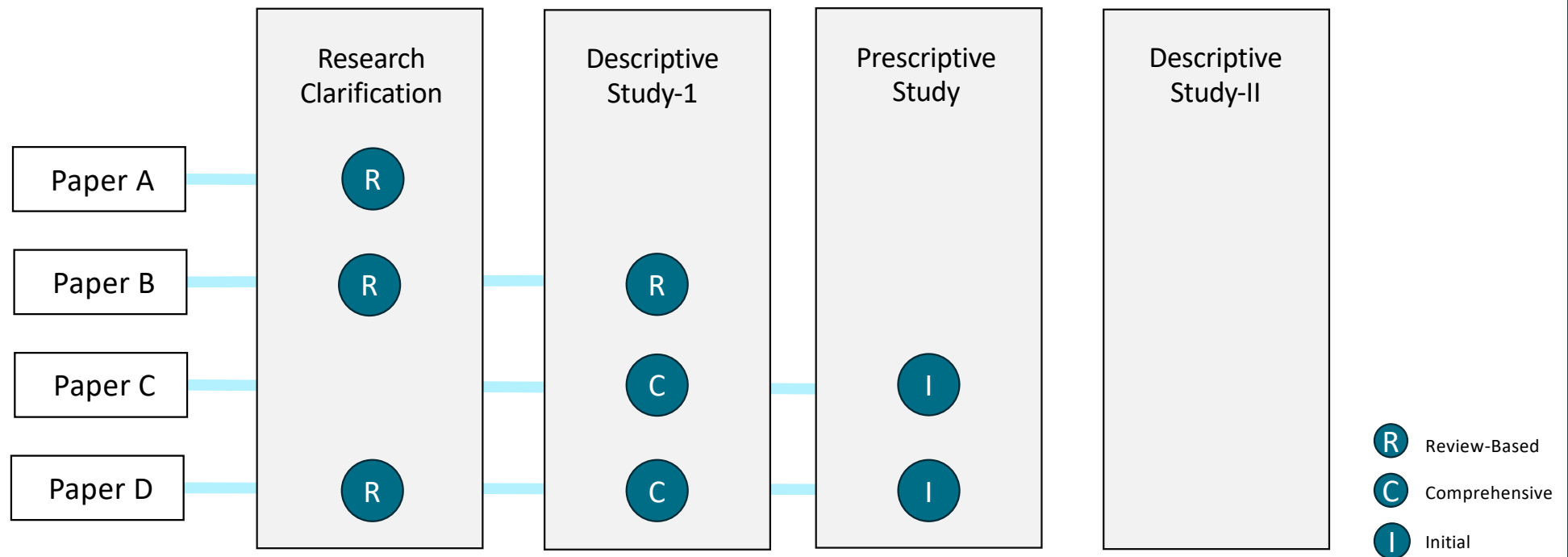


Approach

Participatory  
Action Research



# Research activities

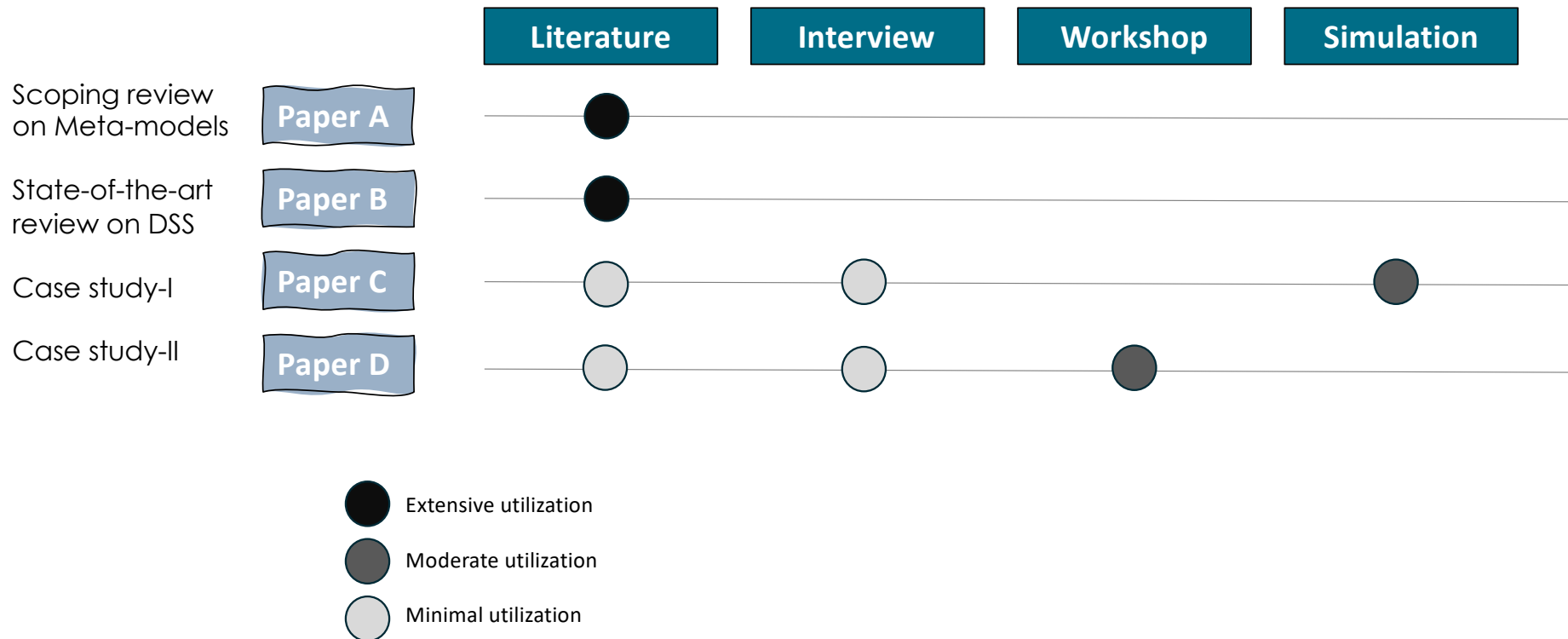


# Case companies



|                             | PAPER C  | PAPER D   |
|-----------------------------|--|---|
| Dimension                   | Case Study I                                       | Case Study II   |
| Industry context            | Off-road machinery, high workload variability      | Shipbuilding, High variety low volume   |
| System characteristics      | Fast, repetitive cycles                            | Long lifecycle, modular configurations  |
| Uncertainty factors         | Operational context variability (availability)     | Newer modular design approaches   |
| Decision support need       | Real-time feedback with reduced computational cost | Real-time feedback, user-friendly environment to explore trade-offs, for non-technical stakeholders too |
| Data utilization – customer | Medium → operational/usage data                    | High → detailed specs   |
| Data utilization – provider | High → rich engineering simulation data            | Medium → sustainability databases, supplemented with AI   |

# Data collection



# Results

# Identification of the challenges



DSS is a socio-technical system

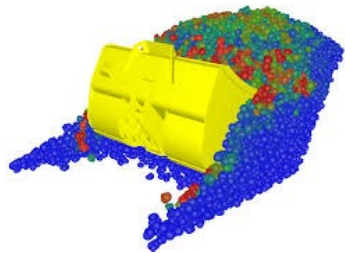
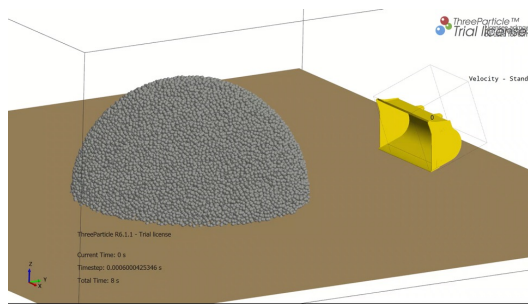
Results focus more on technical aspects

Less focus on social aspect (organizational integration and adoptability)



# Lack of Integration of heterogeneous simulation models

When operating at **various levels of simulation granularity**

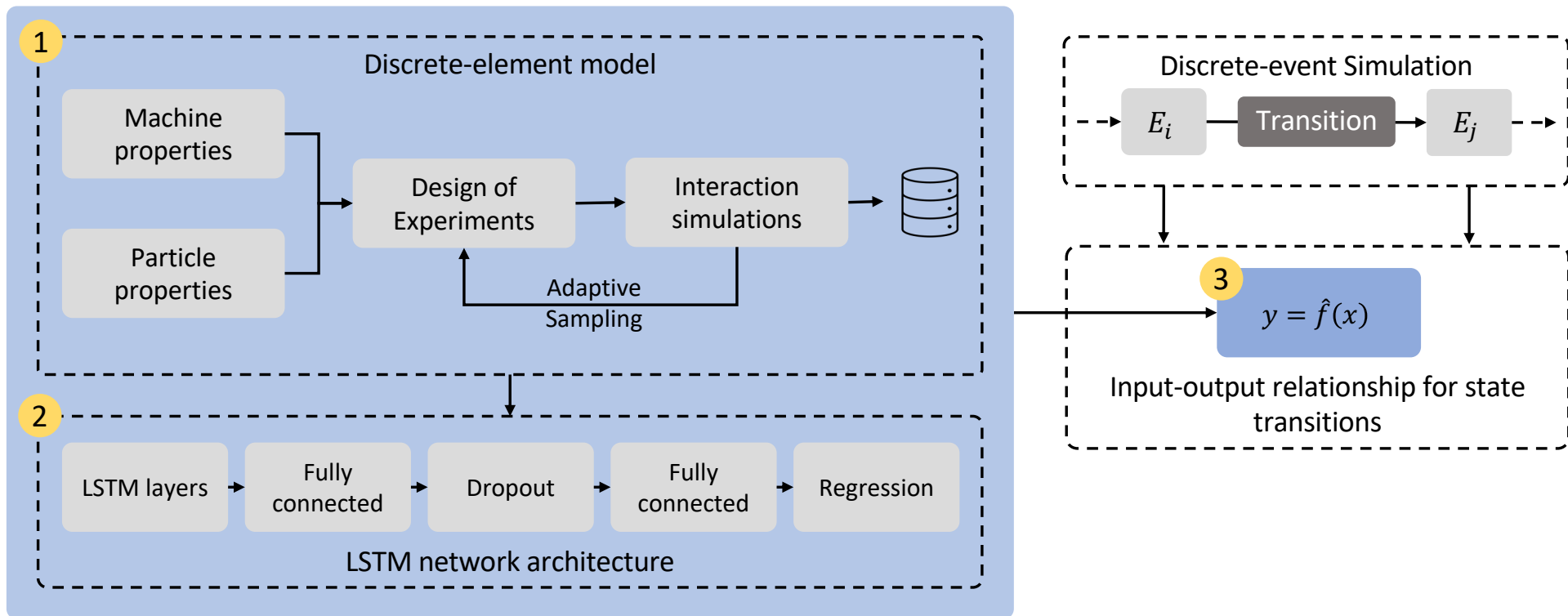


Particle Simulation (DEM)



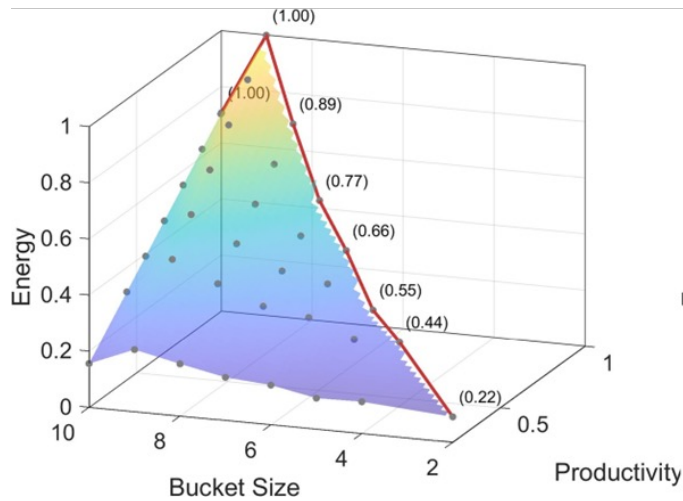
Discrete Event Simulation (DES)  
Fleet of Machines (SoS)

# An approach to bridge simulation granularity? Case Study-I



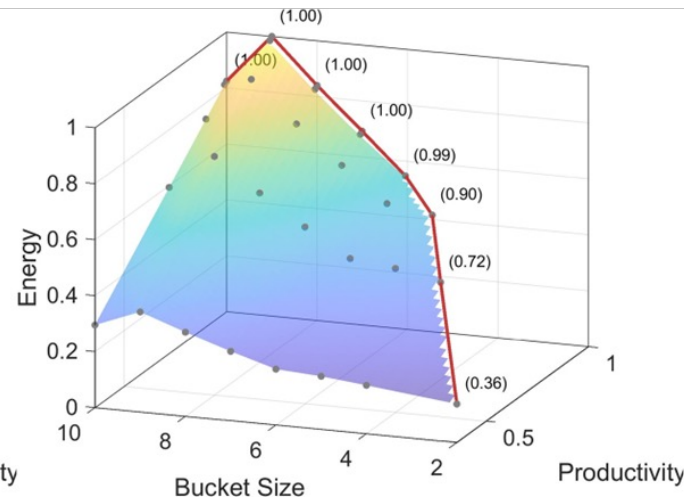
# Decision making in an operational scenario

## Scenario 1



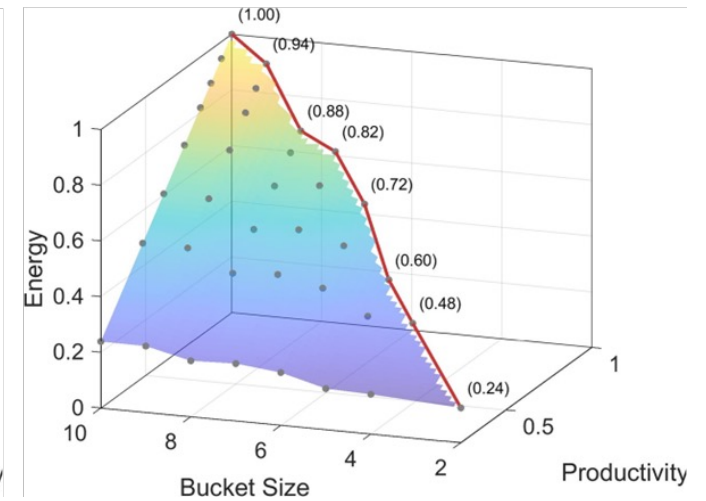
- 8 Haulers (4 pairs)
- 1 pair capacity 20 tons
- Remaining 10 tons

## Scenario 2



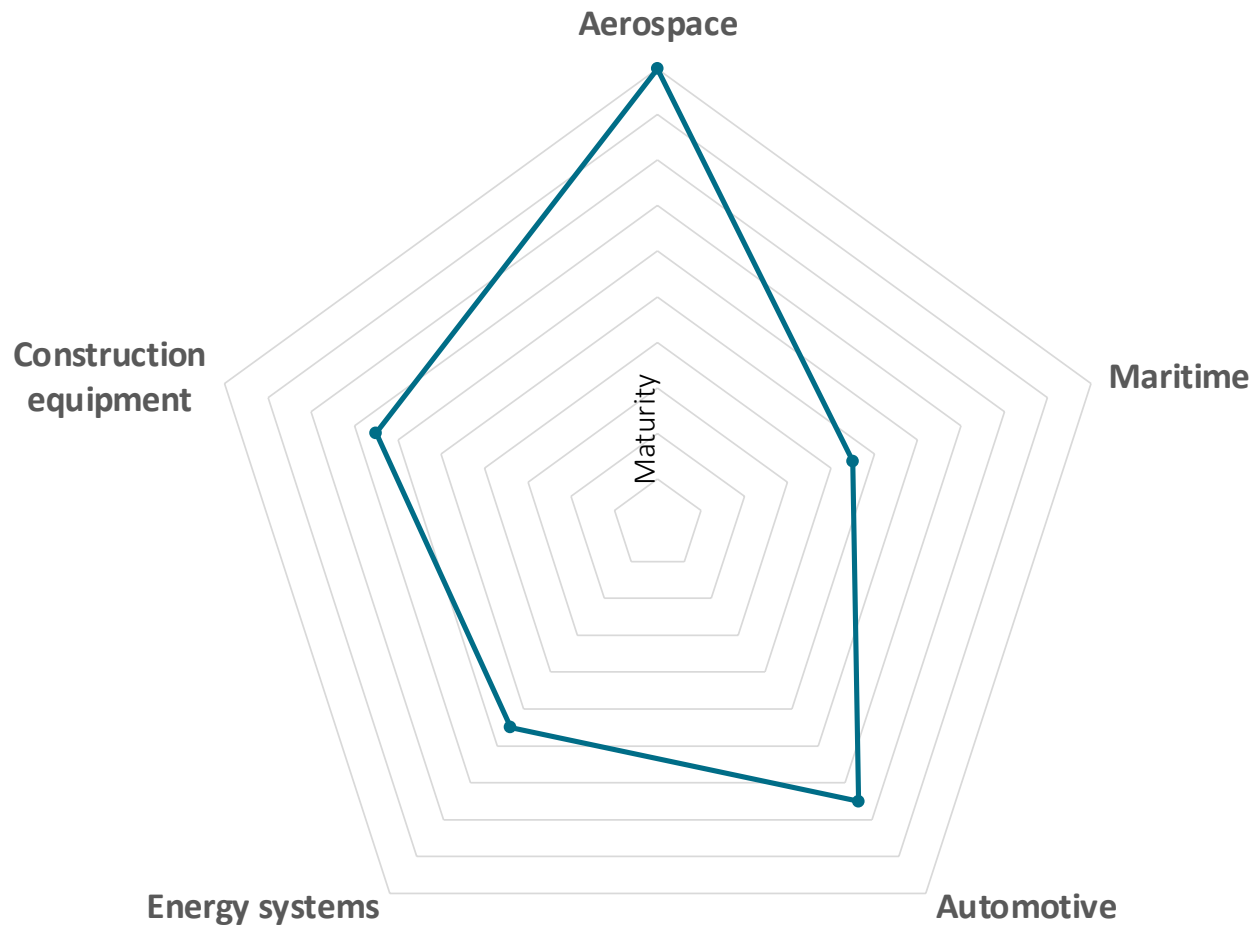
- 4 Haulers (2 pairs)
- 1<sup>st</sup> pair capacity 20 tons
- 2<sup>nd</sup> pair capacity 12 tons

## Scenario 3



- 6 Haulers (3 pairs)
- Combining 15- and 20-tons capacity in each pair

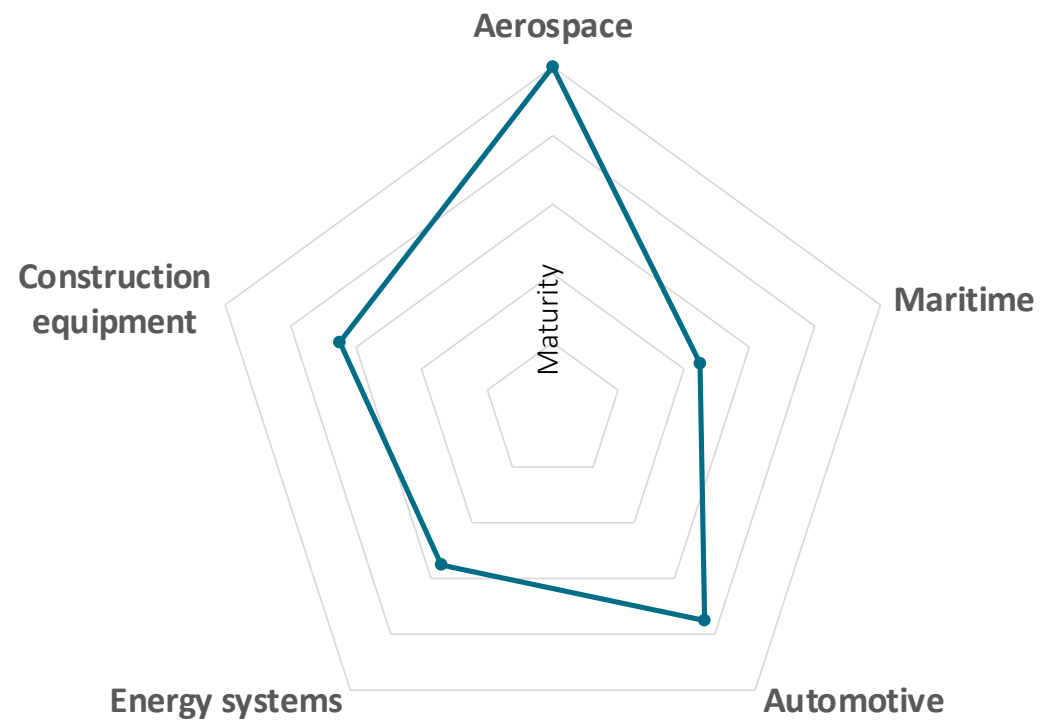
# Discipline-dependent maturity level



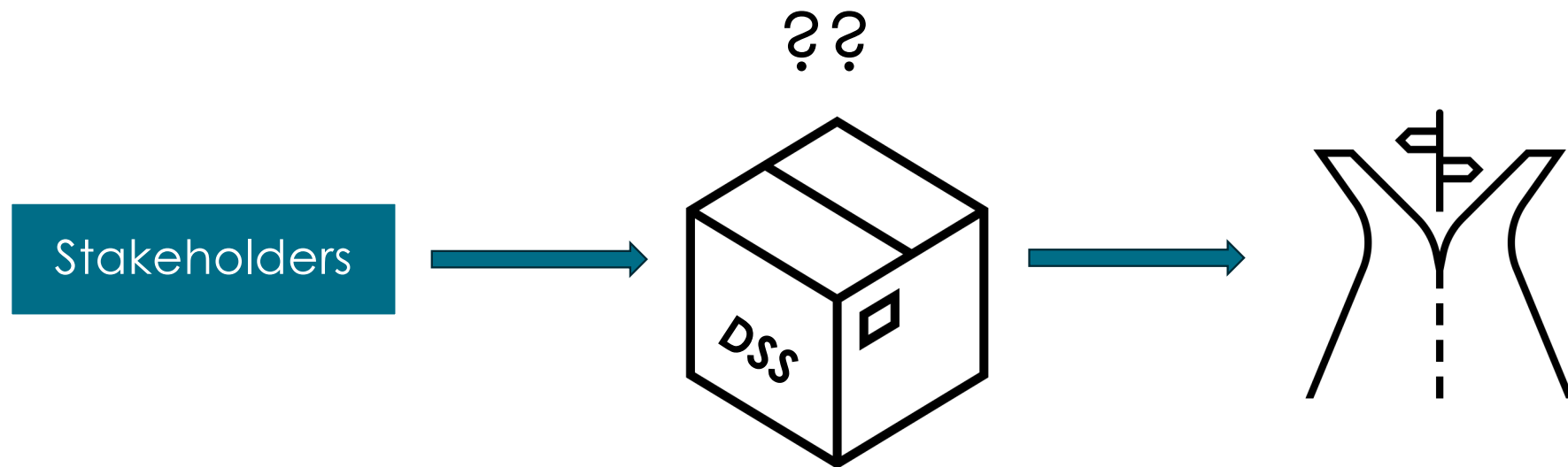
# Discipline-dependent maturity level

## Why?

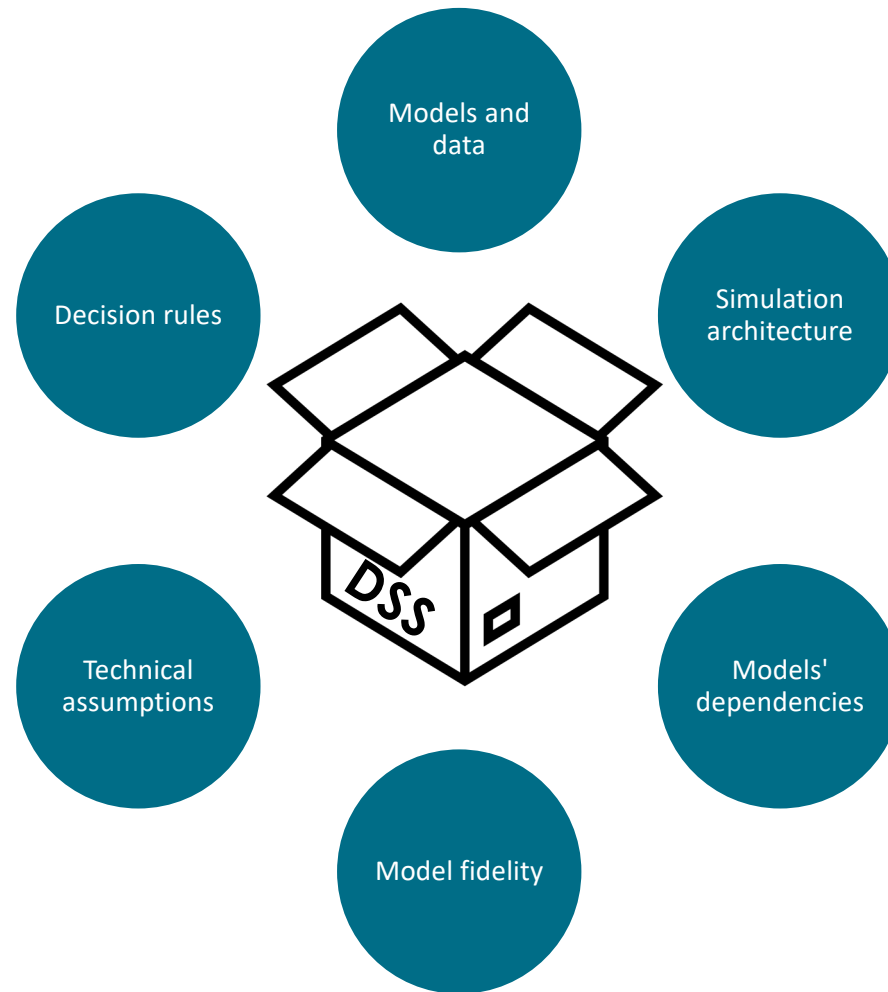
- **Rush for fast paced new product development**
- **Data availability**
- **Methodological factors**
- **Technological Ecosystem**



# Utilization of DSS as 'Black Box'



# Utilization of DSS as 'Black Box'

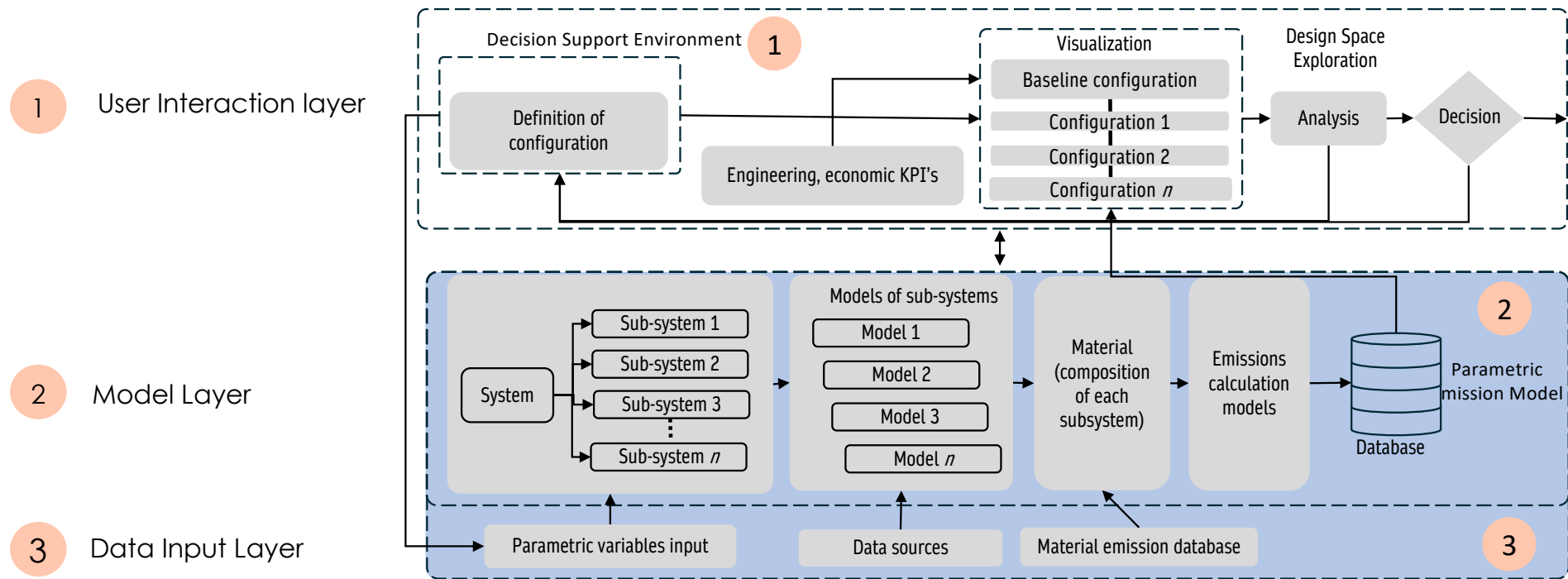


# Preserving the models' efficacy as 'boundary object'

Why it matters?

- **specialist-only models** hinders collaborative decision making
- **Hidden assumptions** and **embedded decision rules** reduces transparency and trust
- **Lack of accessibility** limits collaboration across disciplines

# An approach promoting models' efficacy as 'boundary object'



# Lack of matric to gauge maturity level of models

DSS use multiple computational models with **different validation levels and data quality**

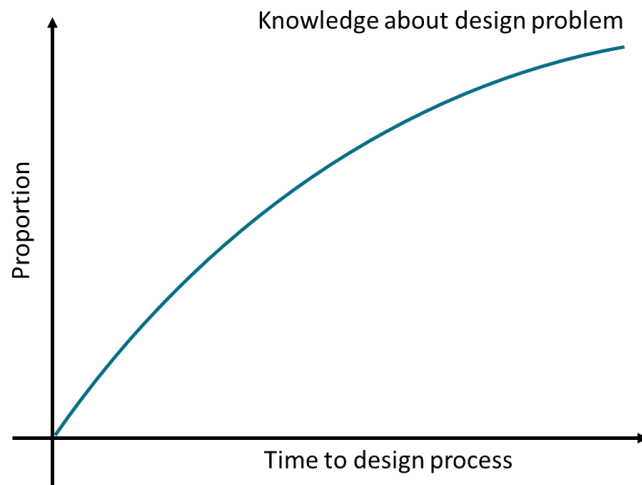
Without maturity gauges decision-makers may **have lower confidence and less trust** on results

Decisions may be **biased** toward “favorable-looking” outputs, even if based on weak models

Non-Technical stakeholders **struggle** to trust DSS results

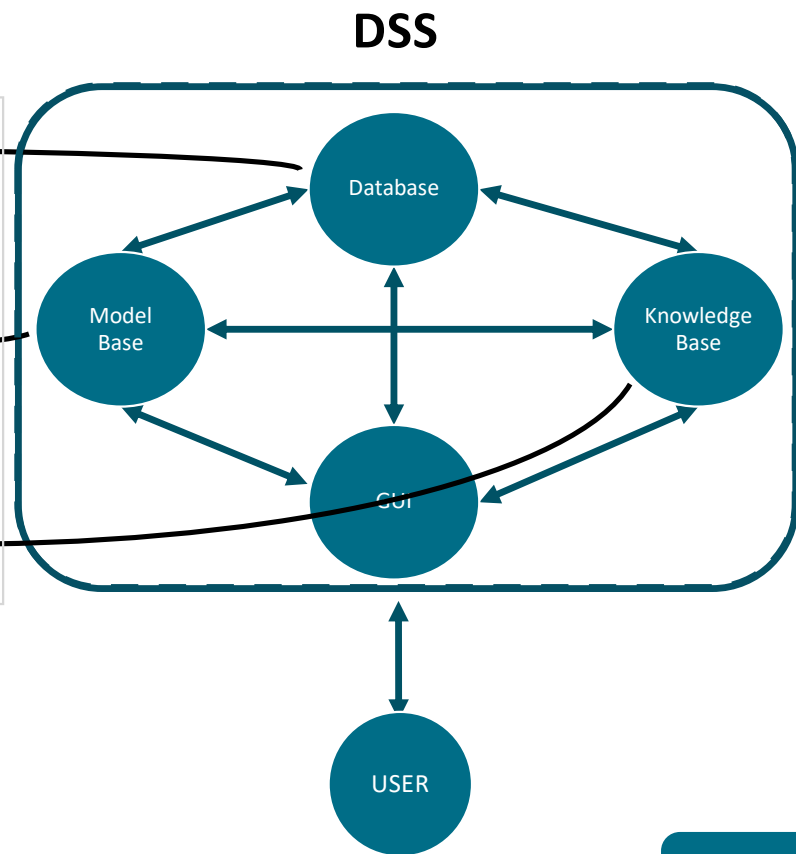
Model Maturity Level concept does exists however **not widely implemented** in DSS. Reliance still mostly on **qualitative expert judgment**

# Lack of Lifecycle management aspect in DSS



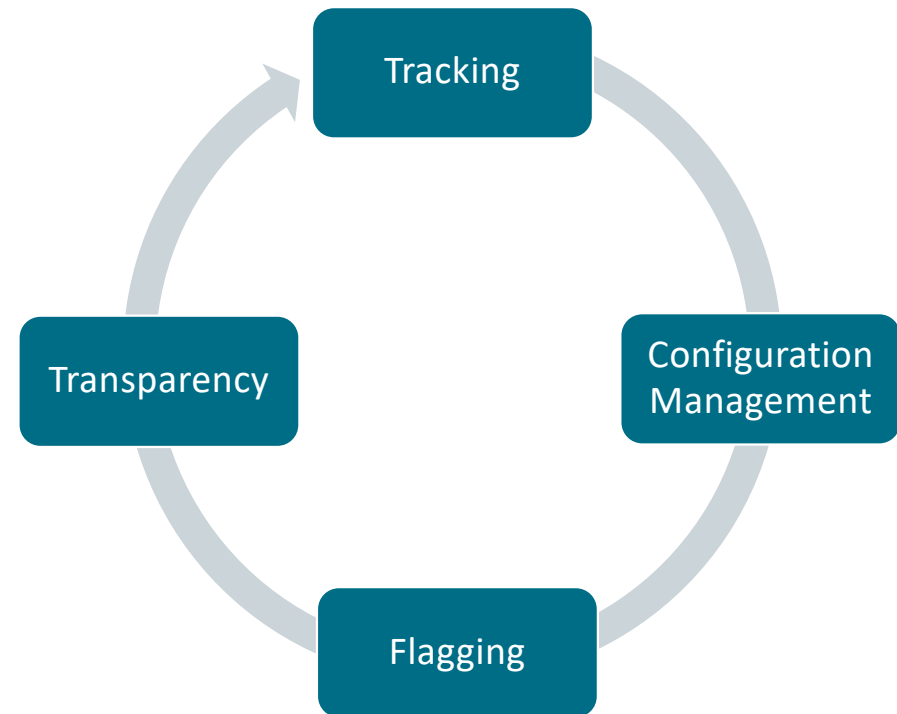
Design Knowledge with time

- **Data**
- **Dependencies**
- **New rules, decision logic**



# DSS as a living, evolving system

- Track and manage sub-model changes and dependencies
- Maintain historical records of model versions
- Flag configurations affected by model updates
- Provide transparency on model origin & validation



# Semantic clarification of the term 'Meta-Model'

# Need for semantic clarification of the term 'Meta-Model'

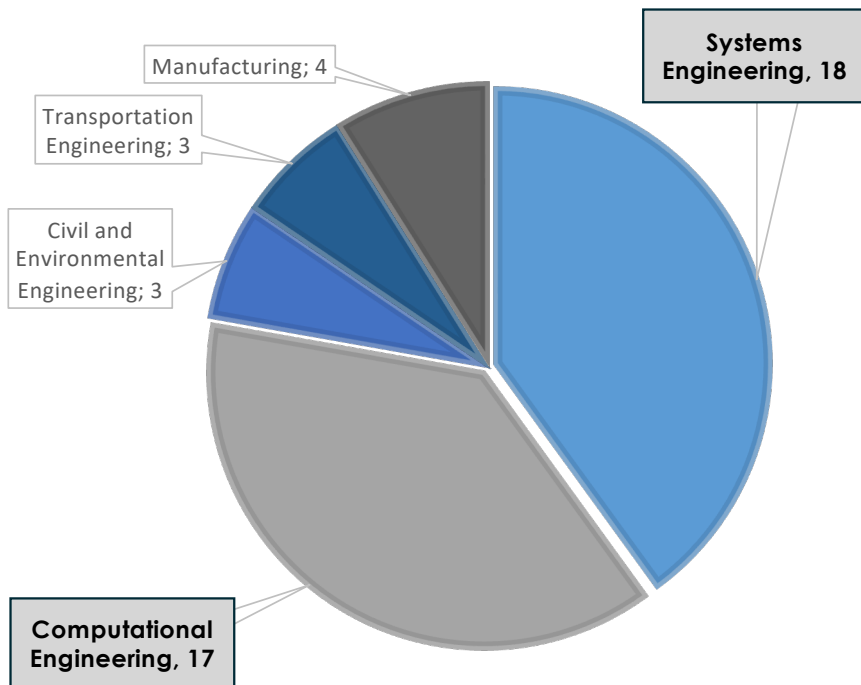
## Problem Identified

- Same term with different semantic interpretations based on application areas
- Causes miscommunication and misinterpretation in Collaborative setting

## Research Need

- Highlight differences in interpretation based on application areas
- Identification of commonalities that exist in literature

# Scoping Review on Meta Models (Paper A)



- Meta model as surrogate or approximate model
- Meta model as a framework or blueprint

# What does the literature says...?

Common ground both act as model of the model but with different roles (governance vs. efficiency)

## Systems Engineering

## Computational Engineering

### Purpose and Function

**Framework** for building specific models within a domain or system

**Surrogates** reducing computational resources. Save time

### Scope

Ensures consistency, coherence, and **standardization**

**Approximates** the complex model's behavior

### Abstraction

Operates at a **higher level** of abstraction, capturing fundamental relationships and concepts

Operates at a **lower level** of abstraction, focusing on mimicking the input-output relationships

### Interpretation

**Offers guidance** for creating models

**Provides approximate predictions** of the complex model's outputs, enabling **quick assessments**

Conclusion

# Addressing the research question

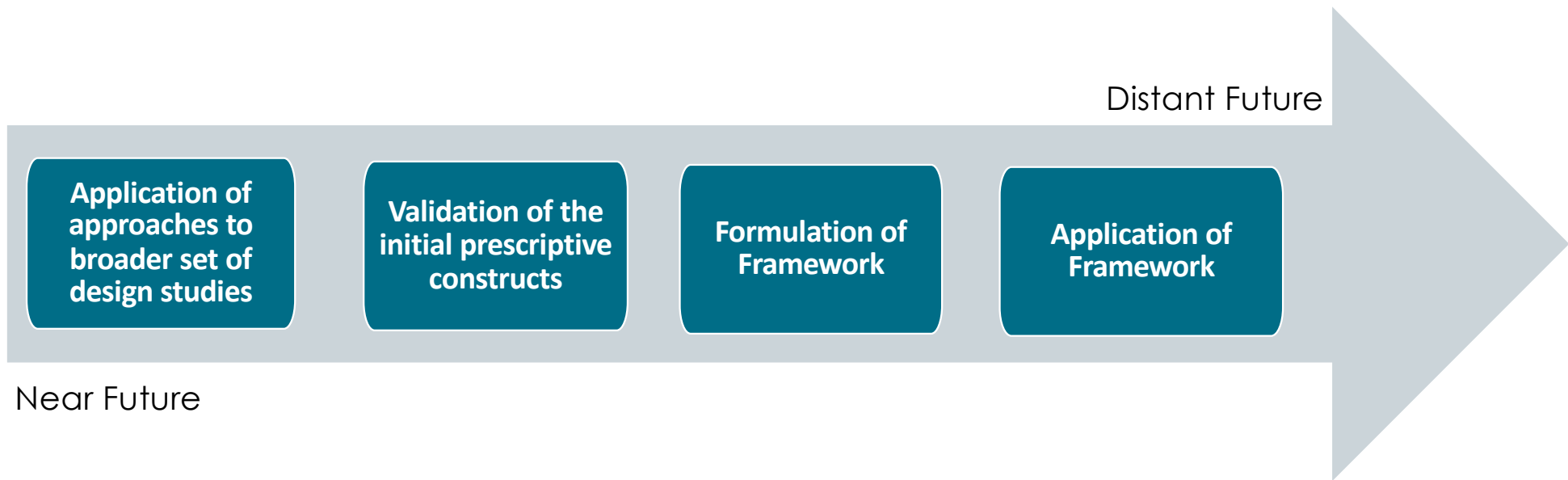
**RQ: What** are the **key challenges** associated with current **model-driven decision support systems** used during early-stage design in complex engineering systems?

The model-driven DSS are socio-technical systems meaning that the challenges extend beyond computational capacity. Some of the **key challenges identified** are as follows:

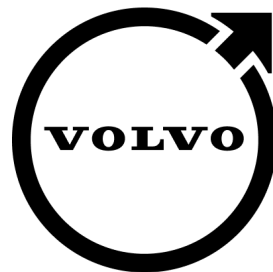
- Integration across heterogeneous models remains a challenge
- Lack of transparency
- Lack of ability to act as boundary object
- Absence of real-time feedback
- Lack of maturity assessment framework
- Insufficient lifecycle management

# Outlook

# Future work – Prescriptive Study and Descriptive study



# Acknowledgements



Thank you!

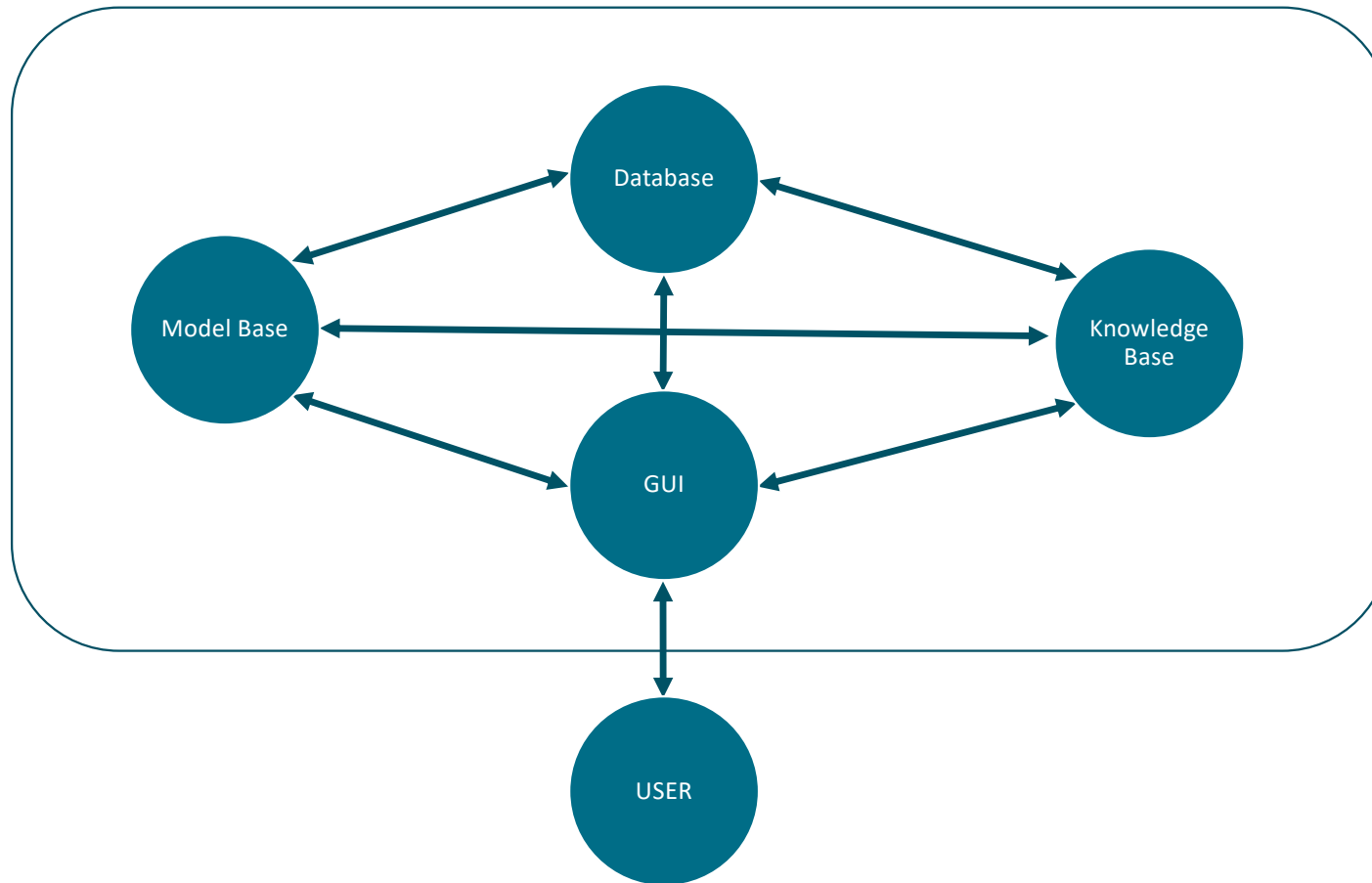


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# Decision Support System



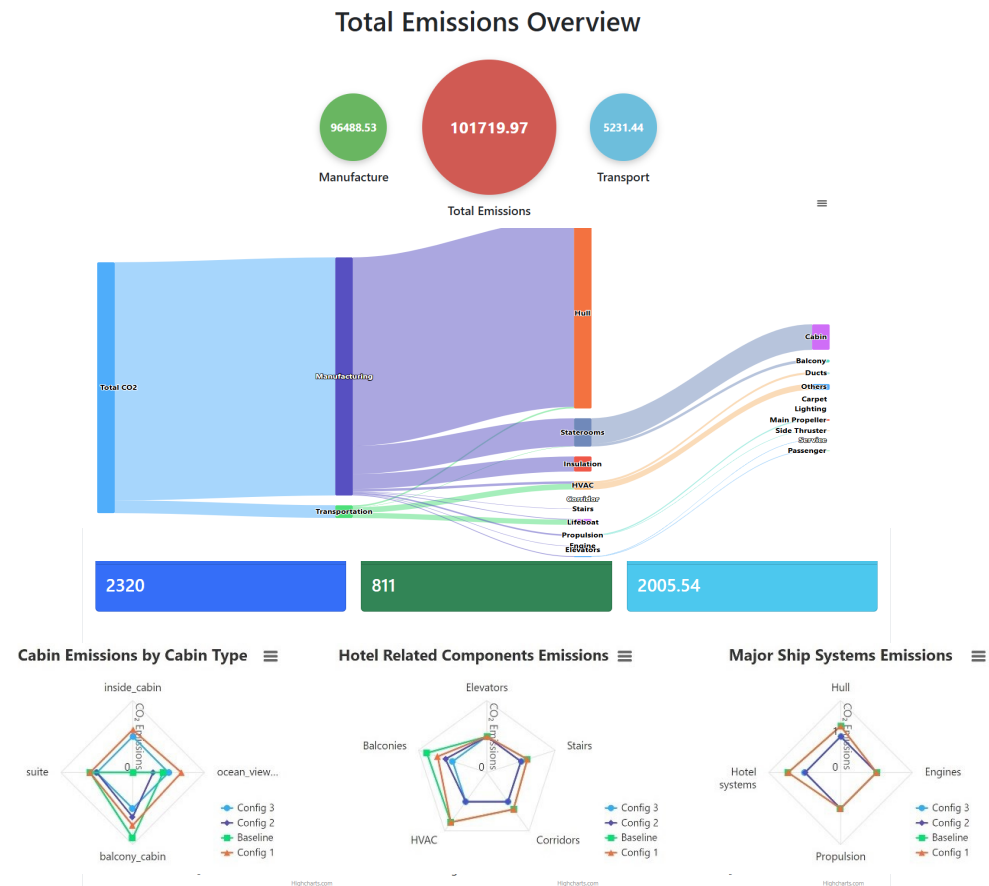
Technical Aspect

Social Aspect

# Promoting models' efficacy as 'boundary object'

|                              |   |
|------------------------------|---|
| Ship Parameters              | ▼ |
| Luxury Level                 | ▼ |
| Cabin Distribution           | ▼ |
| Insulation Parameters        | ▼ |
| HVAC Parameters              | ▼ |
| Corridor Parameters          | ▼ |
| Balcony Parameters           | ▼ |
| Propulsion Parameters        | ▼ |
| Stairs Parameters            | ▼ |
| Elevator Parameters          | ▼ |
| Corridor Lighting Parameters | ▼ |
| Engine Parameters            | ▼ |
| Lifeboat Parameters          | ▼ |

Calculate CO<sub>2</sub> Emissions



# Research Implications

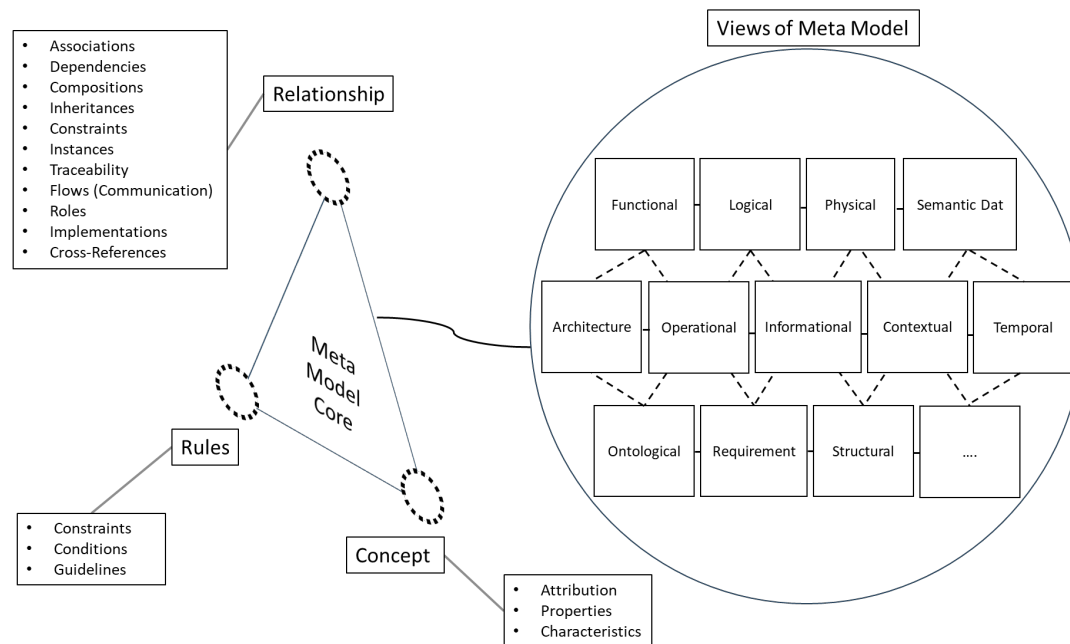
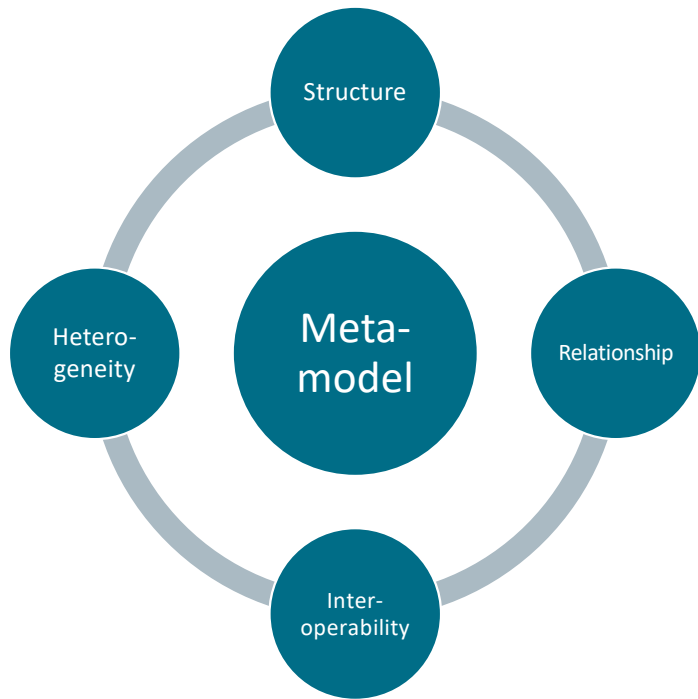
Increase understanding of the practical challenges associated with DSS

A raised awareness of the importance of improving data transparency to enhance stakeholders' confidence

An acknowledgement of the need for structured approaches to manage the evolution, traceability and reliability of simulation models

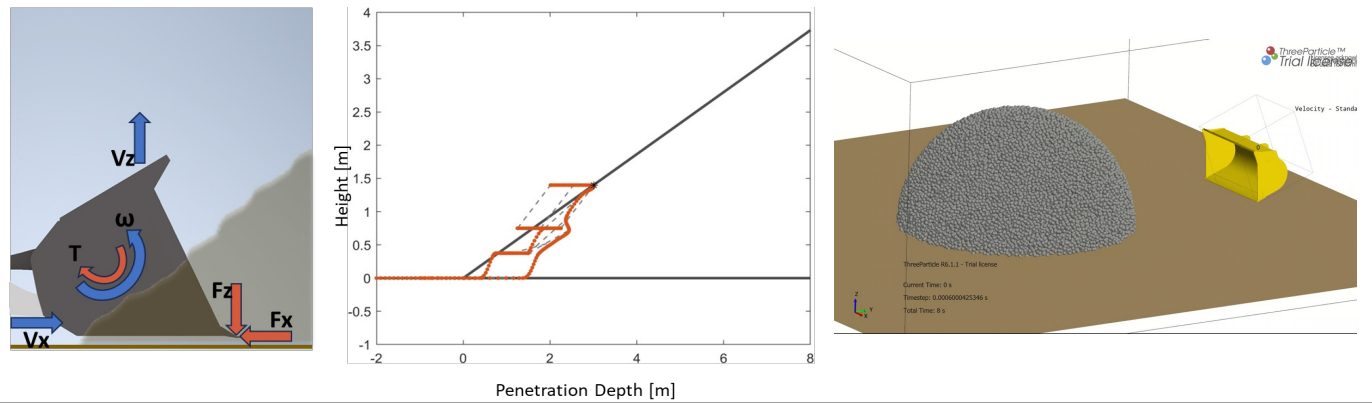
# Meta-Models

Meta-model refers to a framework or representation that captures **the relationships** and **interactions** between **different levels of models** within a complex system

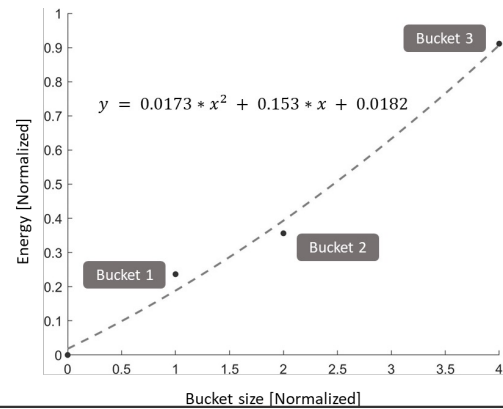
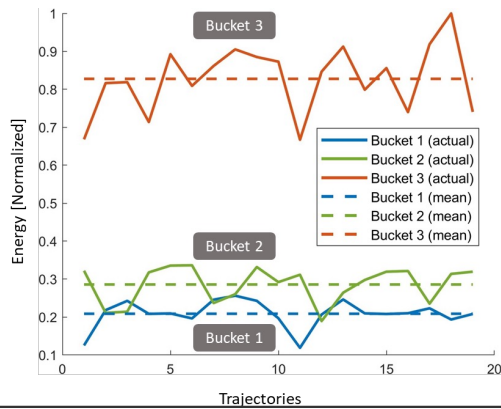


# Integration of heterogeneous simulation models

## DEM



## Surrogate



# Summary findings (Results)

- DSS as socio-technical systems
- Integration of models at varying levels of granularity
- Transparency and accessibility
- Real-time feedback
- Trust and maturity
- Lifecycle management

DSS utility lies in knowledge management, credibility, and adaptability, not just computation

# Appended papers

- **Paper A**

Rehman, M. U., Bertoni, A., Wall, Johan (2025). Clarifying the Concept of Meta-Models for Collaborative Decision-Making in Engineering Complex Systems. Proceedings of PRO-Ve 2025, Accepted for publication

- **Paper B**

Bertoni, A., Juuti, T., & Rehman, M. U. (2024). Decision Support Systems for Engineering High Variety Low Volume Artefacts. Proceeding of NordDesign 2024, 646–654. <https://doi.org/10.35199/NORDDDESIGN2024.69>

- **Paper C**

Rehman, M. U., Machchhar, R. J., & Bertoni, A. (2024). Bridging simulation granularity in system-of-systems : conjunct application of discrete element method and discrete event simulations in construction equipment design. Proceedings of the Design Society, 2705–2714. <https://doi.org/10.1017/pds.2024.273>

- **Paper D**

Rehman, M. U., Bertoni, A. (2025). Model-Driven Scope 3 Upstream (Procurement) CO2 Emission Calculation for the Design Space Exploration of Maritime Vessels. International Conference on Engineering Design (ICED) 2025, Dallas, Texas, USA, Accepted for publication

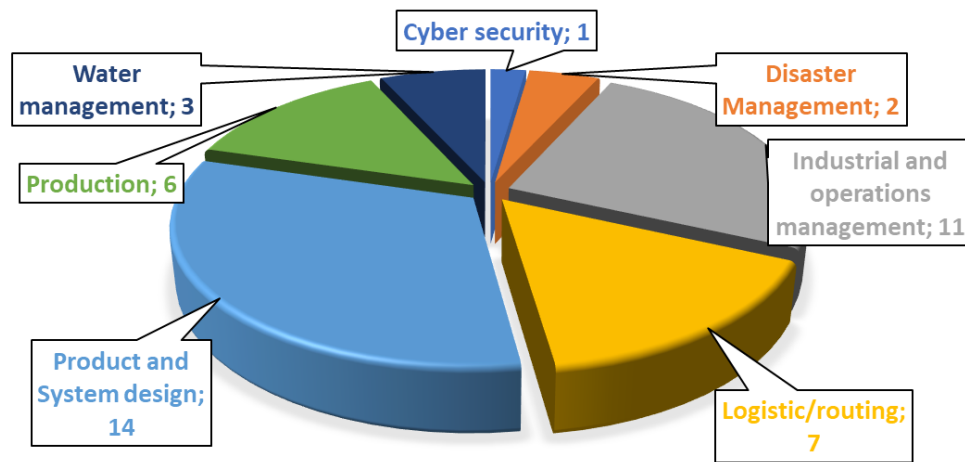
| Ref.                   | Surrogate | Framework | Abstraction | Knowledge | Integration |
|------------------------|-----------|-----------|-------------|-----------|-------------|
| [16] Lin et al.        |           | o         |             |           |             |
| [17] Toffol et al.     |           | o         |             | o         | o           |
| [18] Zhou et al.       | o         |           |             |           |             |
| [19] Broad et al.      | o         |           |             |           |             |
| [20] Shirvani et al.   |           | o         |             |           | o           |
| [21] Cha et al.        |           |           | o           |           |             |
| [22] Ge et al.         |           |           | o           |           | o           |
| [23] Goppert et al.    |           | o         |             |           | o           |
| [5] Medini et al.      |           | o         |             |           |             |
| [9] Bakirtzis et al.   |           | o         |             |           |             |
| [24] Lyazidi et al.    |           | o         |             | o         | o           |
| [25] Haimes et al.     |           | o         |             |           | o           |
| [26] Ghorbani et al.   |           | o         | o           |           |             |
| [27] Raune et al.      | o         |           | o           |           |             |
| [28] Longo et al.      | o         |           |             |           |             |
| [29] Ribeiro et al.    |           | o         |             |           |             |
| [7] Belkadi et al.     |           | o         |             | o         | o           |
| [30] Mostafavi et al.  | o         |           |             |           |             |
| [13] Mcharek et al.    |           | o         | o           | o         | o           |
| [3] Mhenni et al.      |           |           | o           | o         | o           |
| [31] Tekinerdogan      |           | o         | o           |           | o           |
| [32] Woitsch et al.    |           | o         |             |           | o           |
| [33] Can et al.        | o         |           |             |           |             |
| [34] Piriou et al.     |           | o         |             | o         | o           |
| [35] Cao et al.        |           |           |             | o         | o           |
| [36] Zerwas et al.     |           | o         |             | o         | o           |
| [37] Zhao et al.       | o         |           |             |           |             |
| [38] Wang et al.       |           | o         | o           | o         | o           |
| [39] Kieu et al.       | o         | o         |             |           |             |
| [40] Messac et al.     | o         |           |             |           |             |
| [41] Zhu et al.        | o         |           |             |           |             |
| [42] Torregrosa et al. | o         |           |             |           |             |
| [43] Chabanet et al.   | o         |           |             |           |             |
| [44] Lee et al.        | o         | o         |             |           | o           |
| [6] Khosravi et al.    | o         |           |             |           |             |
| [45] Knudde et al.     | o         |           |             |           |             |
| [46] Yonglin et al.    |           | o         | o           |           |             |
| [47] Coelho et al.     | o         |           |             |           |             |
| [48] Touhami et al.    | o         |           |             |           |             |
| [49] Kaseb et al.      | o         |           |             |           |             |
| [4] Aucejo et al.      | o         |           |             |           |             |
| [50] Jensen et al.     | o         |           |             |           |             |

# Pool of papers in Paper B (1)- Product and Service Design

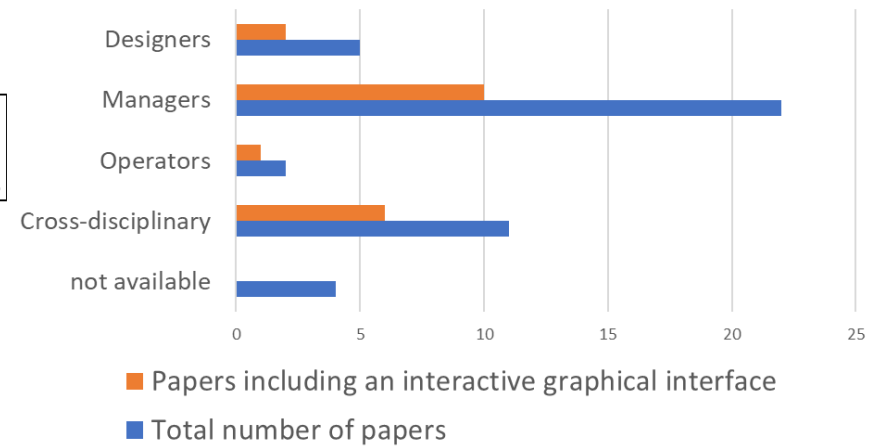
| Authors  | Year | Stage of product development process | Expected users          | Graphical user interface | Metrics for models' reliability | Inclusion of lifecycle-related aspects |
|--|------|--------------------------------------|-------------------------|--------------------------|---------------------------------|--|
| Bertoni A.; Larsson T.; Wall J.; Johansson Askling C.        | 2021 | Conceptual design                    | Cross-disciplinary team | Yes                      | No                              | Yes                                    |
| Bertoni M.; Wall J.; Bertoni A.                              | 2018 | Conceptual design                    | Cross-disciplinary team | Yes                      | No                              | Yes                                    |
| Bibri S.E.   | 2021 | Conceptual design                    | Designers               | No                       | No                              | No                                     |
| Hertz P.; Finke G.R.; Schönsleben P.; Cavalieri S.; Duchi A. | 2014 | Planning                             | Designers               | Yes                      | Yes                             | Yes                                    |
| Kloör B.; Monhof M.; Beverungen D.; Braäer S.                | 2018 | Planning                             | Designers               | Yes                      | No                              | Yes                                    |
| Kuik S.; Diong L.  | 2019 | Operations                           | Cross-disciplinary team | Yes                      | Yes                             | No                                     |
| Lu J.; Yan Z.; Han J.; Zhang G.                              | 2019 | NA                                   | NA                      | NA                       | NA                              | NA                                     |
| Masood T.; Weston R.H.                                       | 2013 | Planning                             | Cross-disciplinary team | No                       | NA                              | NA                                     |
| Power D.J.; Sharda R.  | 2007 | NA                                   | NA                      | NA                       | No                              | No                                     |
| Savrasovs M.; Yatskiv Jackiva I.; Tolujevs J.; Jackson I.    | 2022 | Conceptual design                    | Cross-disciplinary team | No                       | Yes                             | No                                     |
| Song Y.; Thatcher D.; Li Q.; McHugh T.; Wu P.                | 2021 | NA                                   | NA                      | Yes                      | NA                              | NA                                     |
| Wall J.; Bertoni M.; Larsson T.                              | 2020 | Conceptual design                    | Cross-disciplinary team | Yes                      | Yes                             | No                                     |
| Wall J.; Bertoni M.; Larsson T.                              | 2018 | Conceptual design                    | Cross-disciplinary team | Yes                      | Yes                             | No                                     |
| Xie C.   | 2010 | Conceptual design                    | Cross-disciplinary team | No                       | Yes                             | Yes                                    |

# Paper B

CLASSIFICATION OF PAPERS BASED ON FIELD OF APPLICATION



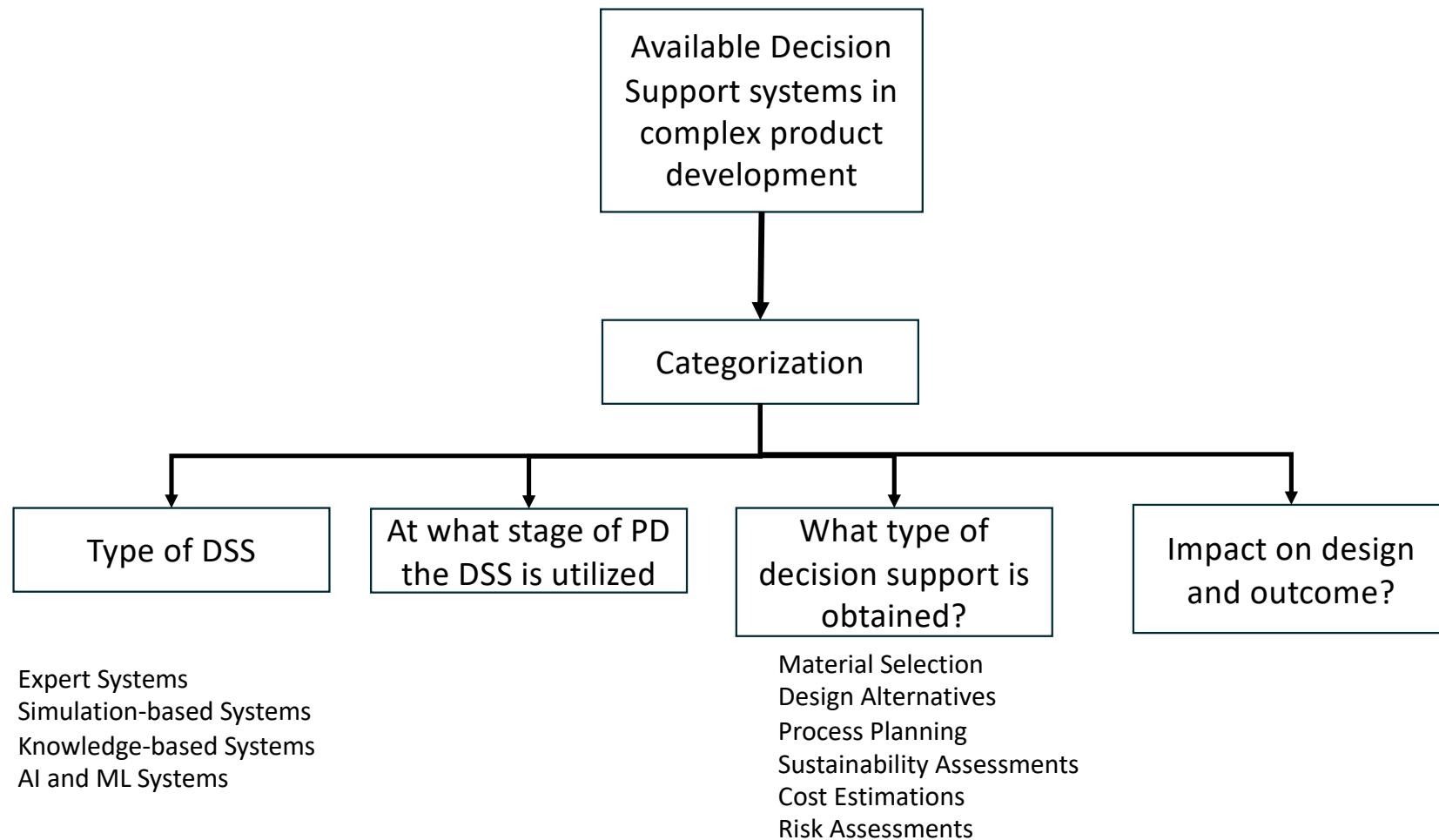
CLASSIFICATION OF PAPERS BASED ON EXPECTED USERS AND PRESENCE OF AN INTERACTIVE GRAPHICAL INTERFACE



## Pool of papers in Paper B (2) – Industrial and Operation management

| Authors  | Year     | Focus area                           | Graphical user interface | Expected Users          |
|--|----------|--------------------------------------|--------------------------|-------------------------|
| Ainbinder I.; David Pinto G.; Rabinowitz G.  | 2019     | Industrial and operations management | No                       | Managers                |
| Alemanly M.M.E.; Ortiz A.; Boza A.; Fuertes-Miquel V.S.  | 2015     | Industrial and operations management | Yes                      | Managers                |
| Jamalnia A.; Gong Y.; Govindan K.; Bourlakis M.; Mangla S.K.   | 2023     | Industrial and operations management | No                       | Managers                |
| Kovács Á.; Rádics J.P.; Kerényi G.   | 2017     | Industrial and operations management | No                       | Operators               |
| Muhammed K.; Farmani R.; Cisternas L.A.; Araya N.  | 2018     | Industrial and operations management | Yes                      | Operators               |
| Naseri N.; Ghiassi-Farrokhfal Y.; Ketter W.; Collins J.  | 2023     | Industrial and operations management | No                       | Managers                |
| Scheller F.; Burgenmeister B.; Kondziella H.; Kühne S.; Reichelt D.G.; Bruckner T.   | 2018     | Industrial and operations management | Yes                      | Managers                |
| Soykan B.; Erol S.   | 2015     | Industrial and operations management | --                       | Managers                |
| Zhen L.; He X.; Wang H.; Laporte G.; Tan Z.  | 2022     | Industrial and operations management | Yes                      | Managers                |
| Dinariyana A.A.B.; Deva P.P.; Ariana I.M.; Handani D.W.  | 2022     | Industrial and operations management | Yes                      | Managers                |
| Abd Rahman M.S.; Mohamad E.; Abdul Rahman A.A.   | 2020     | Production                           | No                       | Managers                |
| Ivatury V.M.K.; Bansa K.B.   | 2022     | Production                           | No                       | Managers                |
| Kuik S.; Diong L.  | 2019 (b) | Production                           | No                       | Managers                |
| Madetoja E.; Rouhiainen E.-K.; Tarvainen P.  | 2008     | Production                           | Yes                      | Cross-disciplinary team |
| Pérez-Salazar M.R.; Aguilar-Lasserre A.A.; Cedillo-Campo M.G.; Posada-Gómez R.; del Moral-Argumedo M.J.; Hernández-González J.C. | 2019     | Production                           | No                       | Managers                |
| Soares A.; Pimentel C.; Moura A.   | 2022     | Production                           | --                       | Managers                |

# What's Paper B all about?



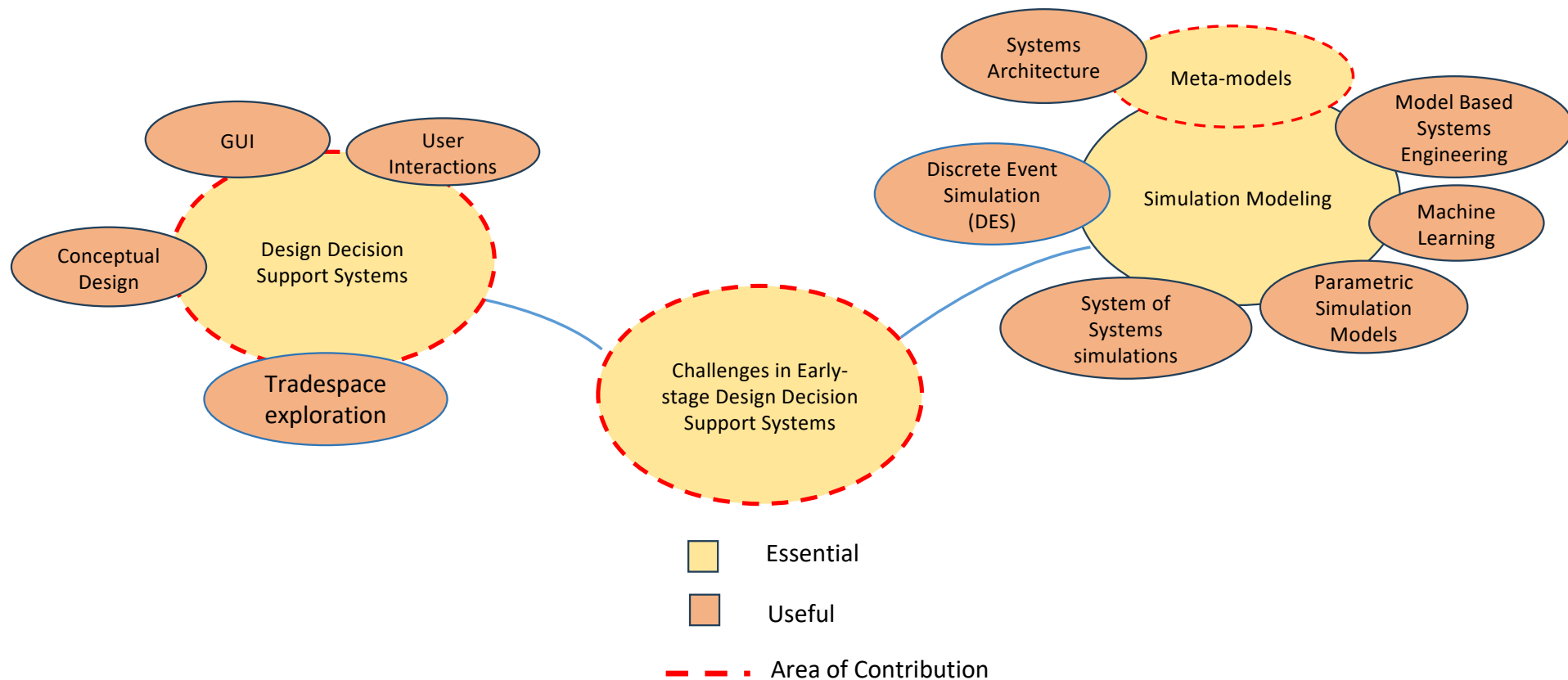
# What makes design science different

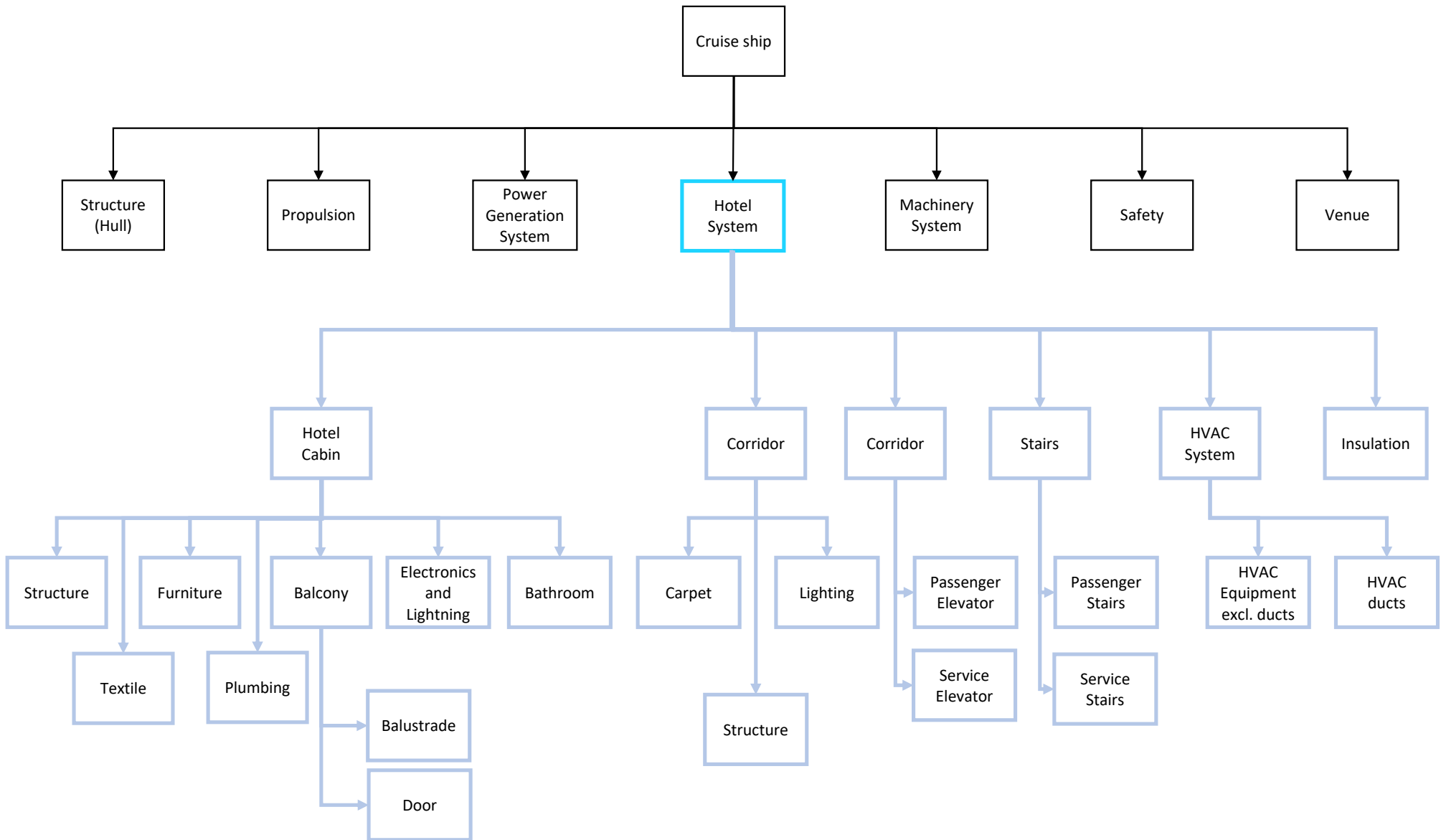
- Design addresses how things should be and is a creative process
- Design creativity is theoretically unbounded, infinite, and simultaneously dependent on and driver of social interactions
- Design theory cannot be deducted generally transferrable from isolated findings to real world

# Research Question

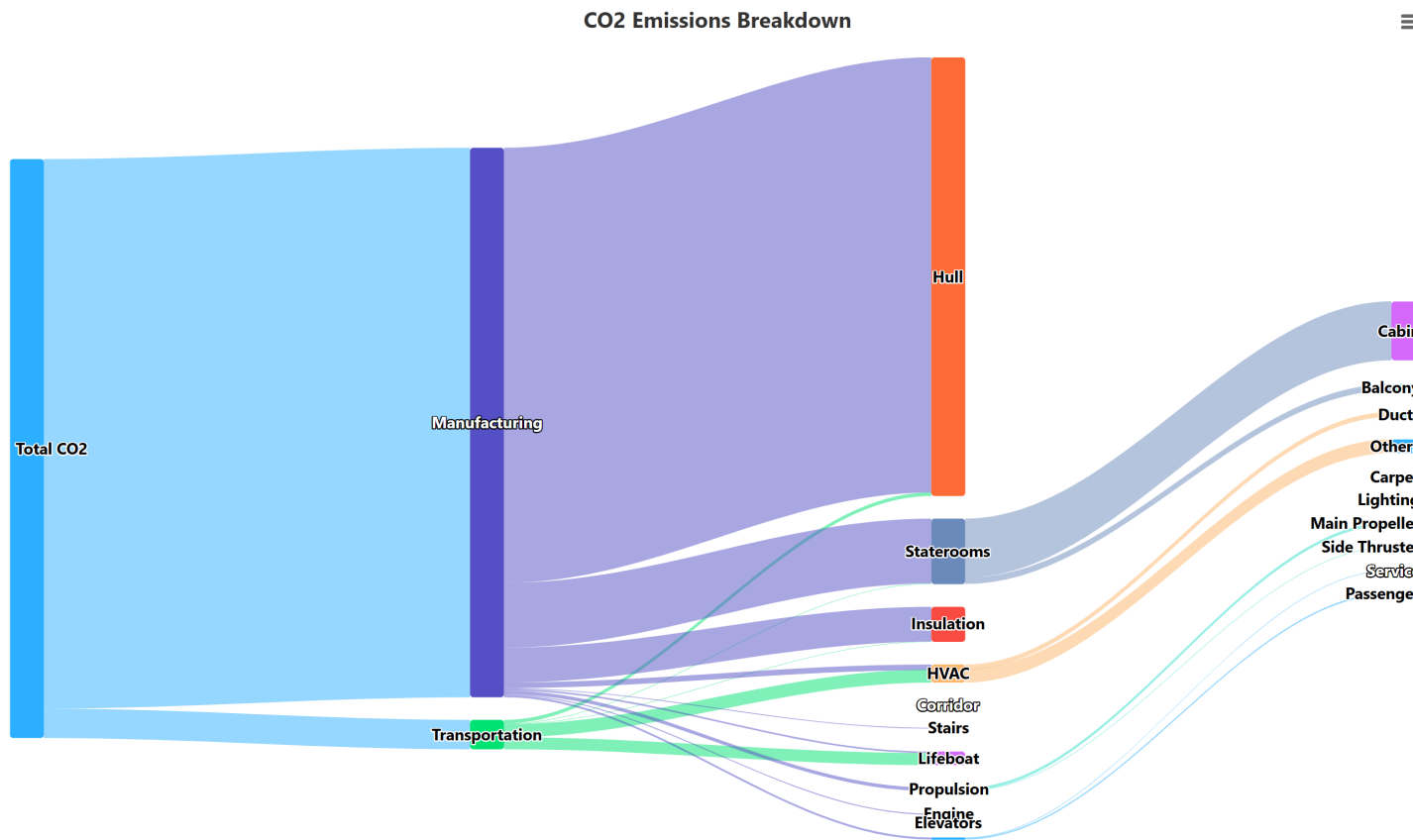
- According to **Yin (1994)** (Robert K. Yin, *Case Study Research: Design and Methods*), research questions can be classified into types based on the form they take:
- Mine is primarily **exploratory**, since it aims to **identify and clarify challenges** rather than explain causal relationships.
- it also has an **analytical/descriptive intent**.

# Area of Relevance and Contribution

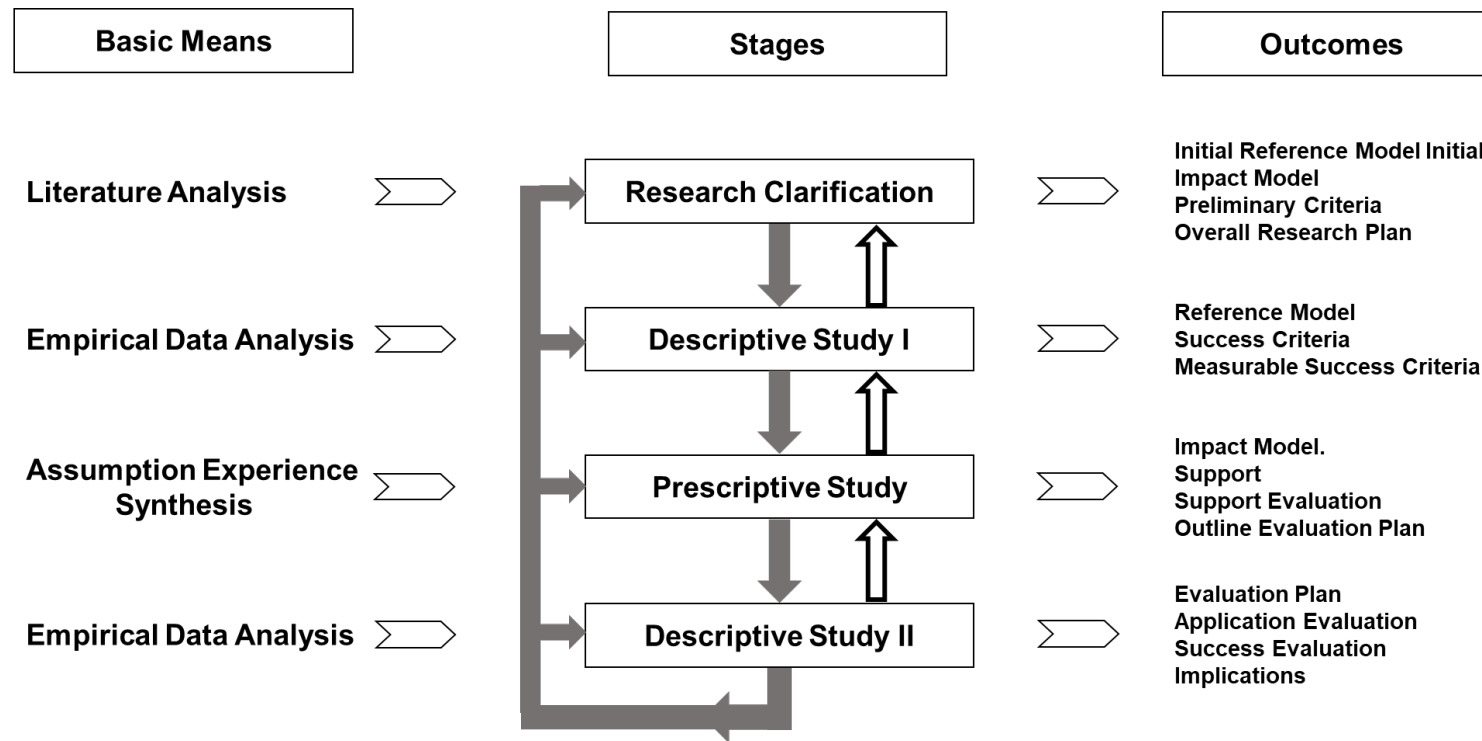




# Sankey Diagram Co2 emissions



# DRM by Blessings and Chakrabarti



# DSS and Design Automation

## Design Automation

- Focus: Efficiency and Repetition
- Automates parameterized tasks (e.g., CAD, CAE, templates)
- Optimizes large design spaces automatically
- Strong at generating solutions, but often black-box
- Limited support for stakeholder communication

## Decision Support Systems (DSS)

- Focus: Informed Decision-Making
- Integrates models, simulations, and sustainability metrics
- Highlights trade-offs & uncertainties
- Ensures transparency, traceability, and explainability
- Models act as boundary objects across stakeholders