Linking Product Configuration & Data Analytics at Siemens CT

Andreas Falkner, August 2017

Shaping the future with a passion for research, technology and innovation: This is the mission of Corporate Technology (CT).

Source: CT - Central research and development unit in Austria, 2017 (siemens.com/innovation)

Our milestones – Over 170 years

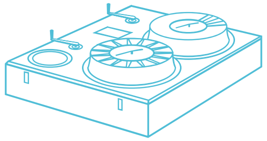
SIEMENS
Ingenuity for life

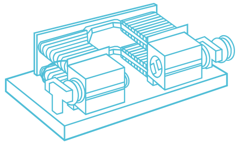
Werner von Siemens

Siemens innovations over 170 years

1816-1892
Company founder, visionary and inventor

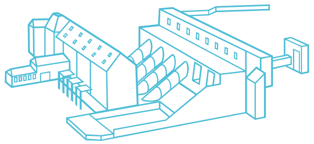
1847
Pointer telegraph

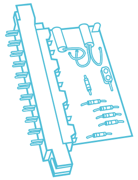




1866
Dynamo

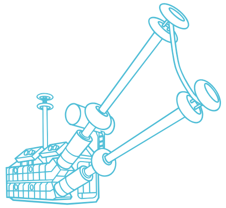
1925
Electrification of Ireland with hydropower

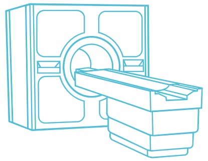




1959
SIMATIC controller

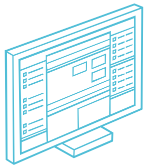
1975
High-voltage direct-current (HVDC) transmission

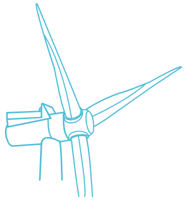




1983
Magnetic resonance tomograph

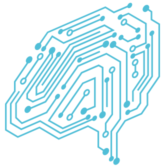
2010
TIA Portal for automation





2012
Field testing of the world's largest rotor at an offshore wind farm

2016
MindSphere introduced as the digitalization platform for all industries



Our innovative power in figures – Siemens as a whole and Corporate Technology

SIEMENS
Ingenuity for life

Expenditures for research and development

€4.7 billion
Expenditures for R&D in fiscal 2016

33,000
R&D employees[1]

Inventions and patents – securing our future

7,500
inventions[1]

3,500
patent applications[1]

University cooperation – our knowledge edge

9
CKI universities[2]

16
Principal partner universities

1 In fiscal 2016
2 Centers of Knowledge Interchange

Corporate Technology – Our competence center for innovation and business excellence[3]

7,400
employees worldwide

4,800
software developers

1,600
researchers

400
patent experts

3 Employee figures: As of September 30, 2016

Our focal points –
Corporate Technology at a glance

SIEMENS
Ingenuity for life

Research in Digitalization and Automation

Research and pre-development work covering all Siemens-relevant areas in digitalization and automation

Research in Energy and Electronics

Research and pre-development work covering all Siemens-relevant areas in energy/electrification, electronics, new materials and manufacturing methods

Technology and Innovation Management

- Siemens' and CT's technology and innovation agenda
- Standardization and technical compliance
- Provision of technical publications

Corporate Technology (CT)

CTO – Roland Busch

University Relations

- Management of the research partner portfolio
- Engagement management with top research partner

Corporate Intellectual Property

- Protection and defense of intellectual property (IP)
- IP licensing & commercialization
- Trademark protection

Development and Digital Platforms

- Software, firmware, and hardware engineering
- Horizontal and vertical product and system integration

Business Excellence and Quality Management

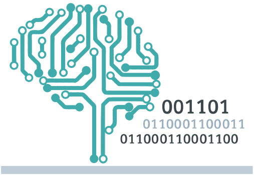
- Siemens Operating Model: excellence in PLM, SCM, project business and service
- Quality management

Our focal points: Digitalization and automation – Securing and extending technology leadership

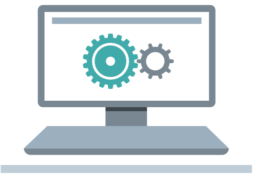
SIEMENS
Ingenuity for life

- We connect the real and virtual worlds. We continuously improve our ability to translate signals from field sensors into meaningful data, to enhance these data with design information and to provide valuable information to system designers and operators.
- Such digital services offer our customers higher or even guaranteed availability, among other things
- Handling data in a secure and confidential manner is a major prerequisite for this
- A digital twin of a real-world system throughout its lifecycle allows us to simulate and optimize it before and after commissioning. This reduces the need for time-consuming and costly prototype construction
- Autonomous systems solve complex tasks in uncertain environments and safely interact with humans
- The industrial Internet of Things spans all stages of industrial production. Products and systems generate data, communicate with each other, and acquire new functionalities even when already in use

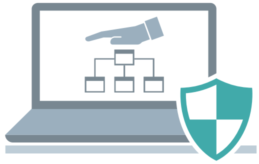
Sensing and monitoring



Data analytics and data management

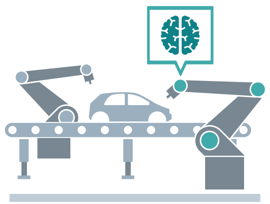


Software and systems

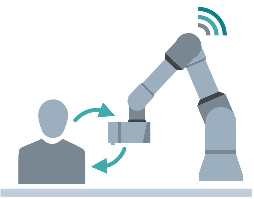


IT security

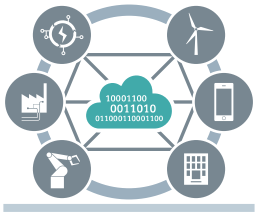
Simulation-driven virtual engineering



Autonomous systems



Human-machine collaboration



Industrial Internet of Things

Research Group "Configuration Technologies"
Correct and efficient configuration solutions

Our tools and technologies help to configure big and complex systems across many domains: rail automation, metals, building technologies, smart factories, healthcare.

We offer deep expert know-how in modeling and handling all tasks related to product configuration along the product lifecycle (design and modeling, sales, engineering, modernization and service).

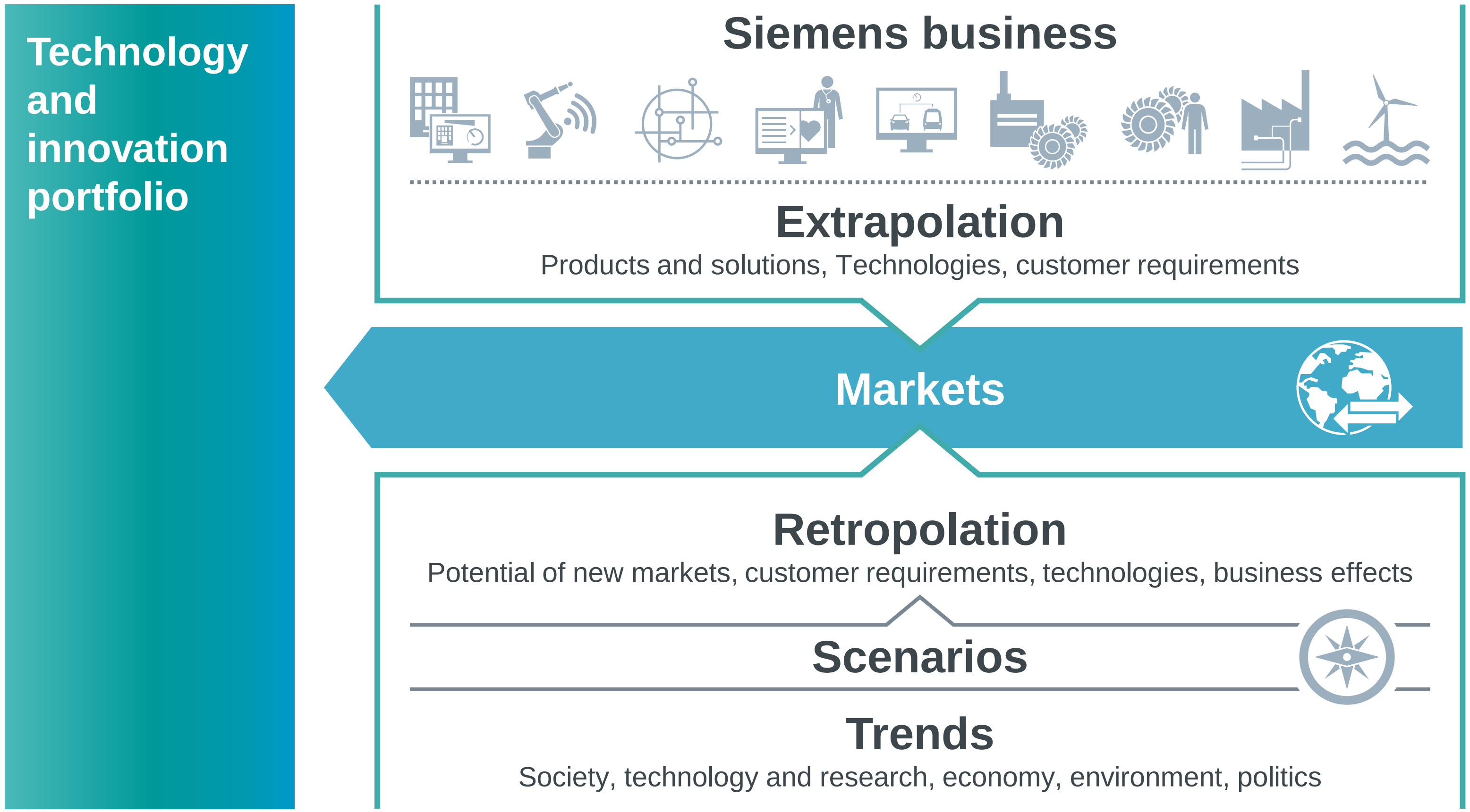
Our expertise in advanced data analytics and our Smart ICT ecosystem enables Seestadt Aspern Vienna to gain new insights into the combination of building automation and smart grid domains.

We successfully combine data analytics and configuration know-how to enhance the quality and the performance of data exploration tasks and to improve the configuration process with new insights.

Our focal points: Innovation strategy – Shaping Siemens' technology and innovation agenda

SIEMENS
Ingenuity for life

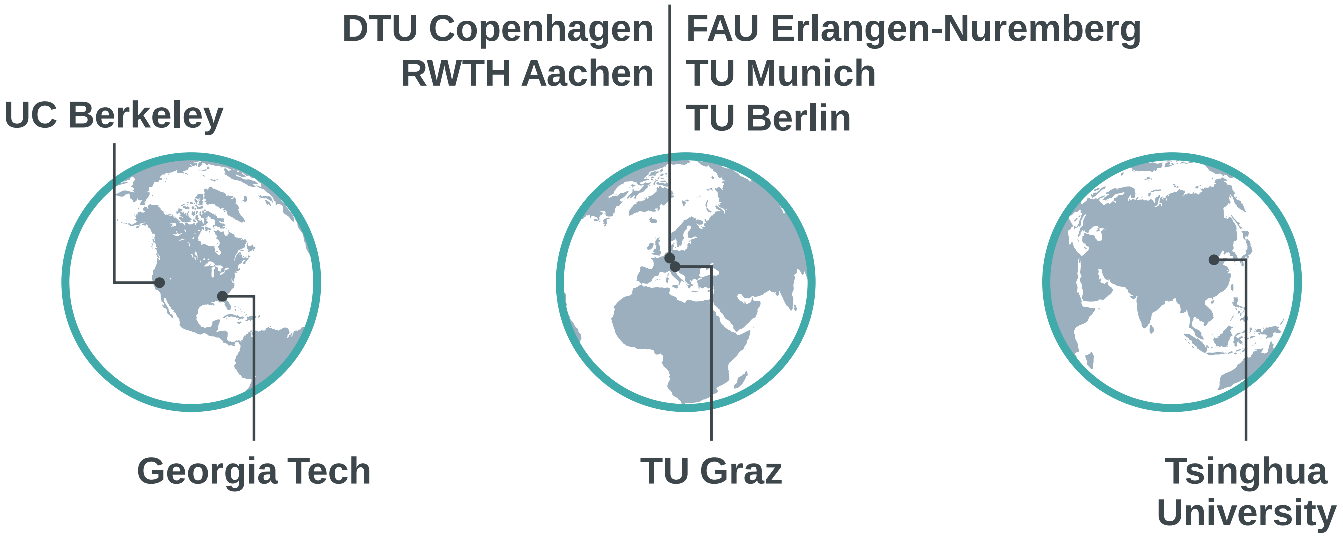
- We analyze trends and novel technologies, develop scenarios for our core markets and recommend adjustments to the Company's innovation and technology agenda
- We assess Siemens' innovative power and the impact of disruptive changes in the spirit of Joseph Schumpeter
- We elaborate and represent the Company's position in matters of research policy
- We coordinate Siemens' standardization activities across Divisions and regions, and ensure compliance with technical law
- We provide the R&D community at Siemens with technical publications



Our focal points: University relations – Overcoming groupthink and tapping potential

SIEMENS
Ingenuity for life

- We network with leading universities and non-university research institutes around the world
- With Open Innovation, we strengthen Siemens' innovative power and tap the potential of a networked, open company
- We link the industrial and academic worlds and thus promote intensive research and recruiting activities
- Our collaboration with nine top universities and the "Centers of Knowledge Interchange" (CKIs) that we set up there exemplify this effort



9 CKI universities

16 Principal partner universities

Research Group "Configuration Technologies"
Selection of recently funded projects

SIEMENS
Ingenuity for life

- **COSIMO**: Collaborative Configuration Systems Integration and Modeling
  http://cosimo.big.tuwien.ac.at/
- **HINT**: Heuristic Intelligence
  http://isbi.aau.at/hint/
- **OpenReq**: Intelligent Recommendation & Decision Technologies for Community-Driven Requirements Engineering - http://openreq.eu/
- **SCDA**: Smart City Demo Aspern
  http://www.ascr.at/foerderungen/scda/
- **SHAPE**: Safety-critical Human- & Data-centric Process Management in Engineering Projects
  https://ai.wu.ac.at/shape-project/index.html
- **Supersede**: Data Analytics for Software Evolution and Adaption
  https://www.supersede.eu/

Andreas Falkner
Senior Key Expert

Phone:
+43 664 80117 35932

E-mail:
andreas.a.falkner@siemens.com

Herwig Schreiner
Head of Research Group

Phone:
+43 664 80117 35465

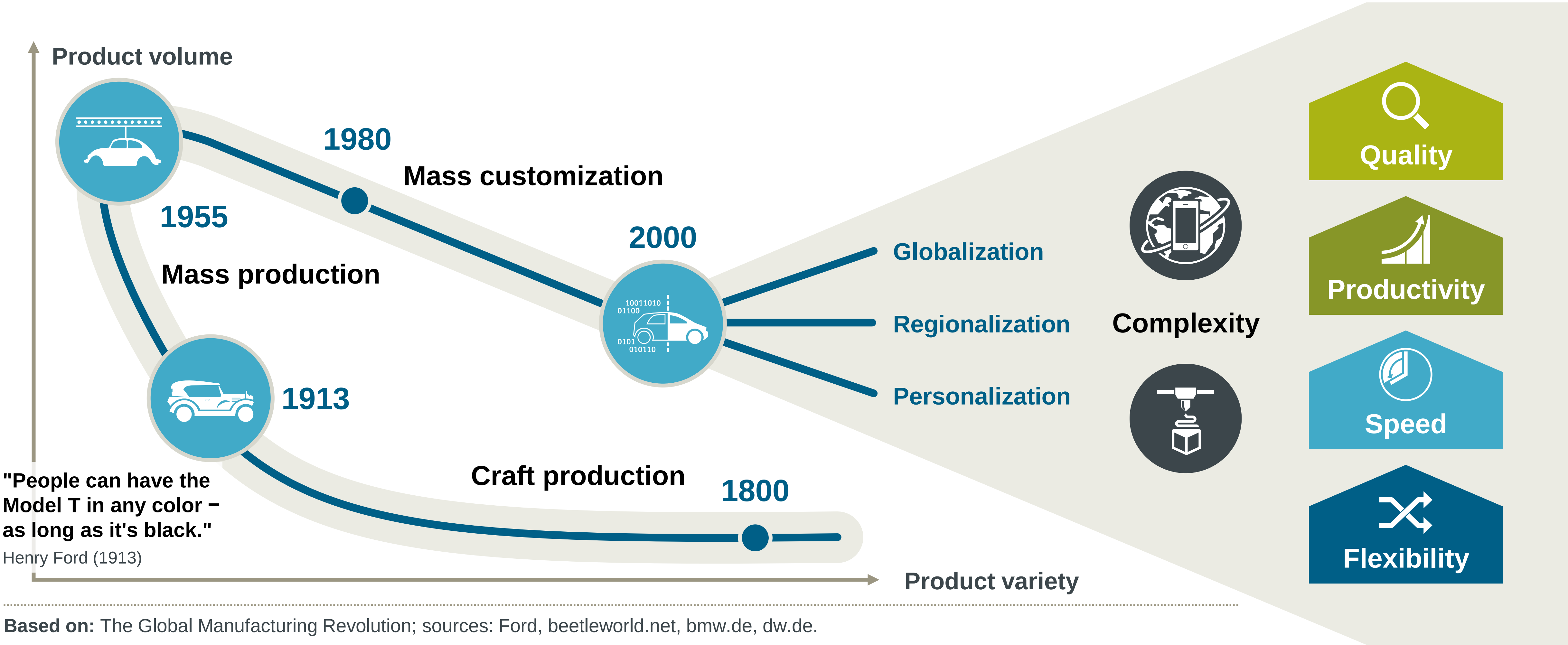
E-mail:
herwig.schreiner@siemens.com

With our innovations and technologies, we set standards for existing and future markets, so that Siemens can remain successful over the long term. Concrete examples show how Corporate Technology contributes to this.

Source: Volker Tresp, Towards Industrial AI, June 2017

Industrie 4.0:
Cyber-physical systems, Internet-of-Things, Self-X

SIEMENS
Ingenuity for life



Based on: The Global Manufacturing Revolution; sources: Ford, beetleworld.net, bmw.de, dw.de.

Industrie 4.0 is already being practiced today in Germany

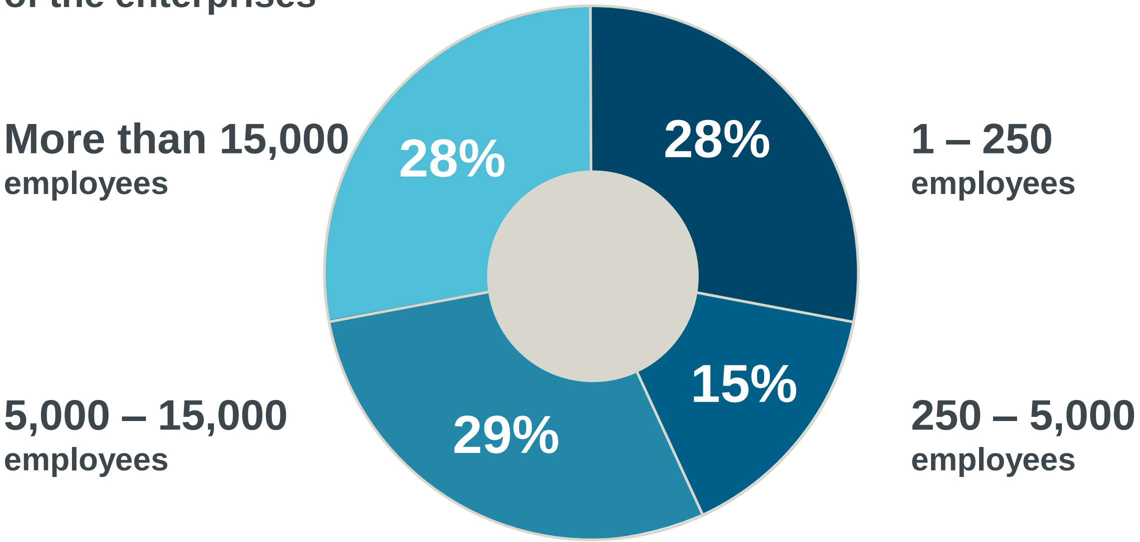
SIEMENS
Ingenuity for life

PLATTFORM INDUSTRIE 4.0

>260 examples of Industrie 4.0 applications and products …

… from large and small enterprises in a wide range of different industry sectors.

Number of employees
of the enterprises



Multiple choices possible

Source: Plattform Industrie 4.0

Example: Siemens AG, Berlin Gas Turbine Factory – 3D printing of gas turbine components

SIEMENS
Ingenuity for life

The laser sintering process can be used to produce small batches at a lower cost and much more quickly than using the costly casting process.

This process is used to make prototypes in order to integrate the testing of certain gas turbine components into the product development process. Now even aggressive component designs can be quickly evaluated and sent back to the design cycle. The result is greater efficiency increases.

"The innovative selective laser sintering process **shortens production times** compared to conventional production processes, so much so that function-critical components can already be **tested during the product development** stage."

Sebastian Piegert, Siemens AG.

Source: Platform Industrie 4.0, Siemens AG, Berlin Gas Turbine Factory.

Example: Data analytic supports optimization machines – e.g. improved efficiency of wind parks (Project ALICE*)

SIEMENS
Ingenuity for life

More than 200 GB of sensor data sensors from ≈ 7.800 wind parks

Early detection of divergent behavior

Autonomous learning with Neural Networks

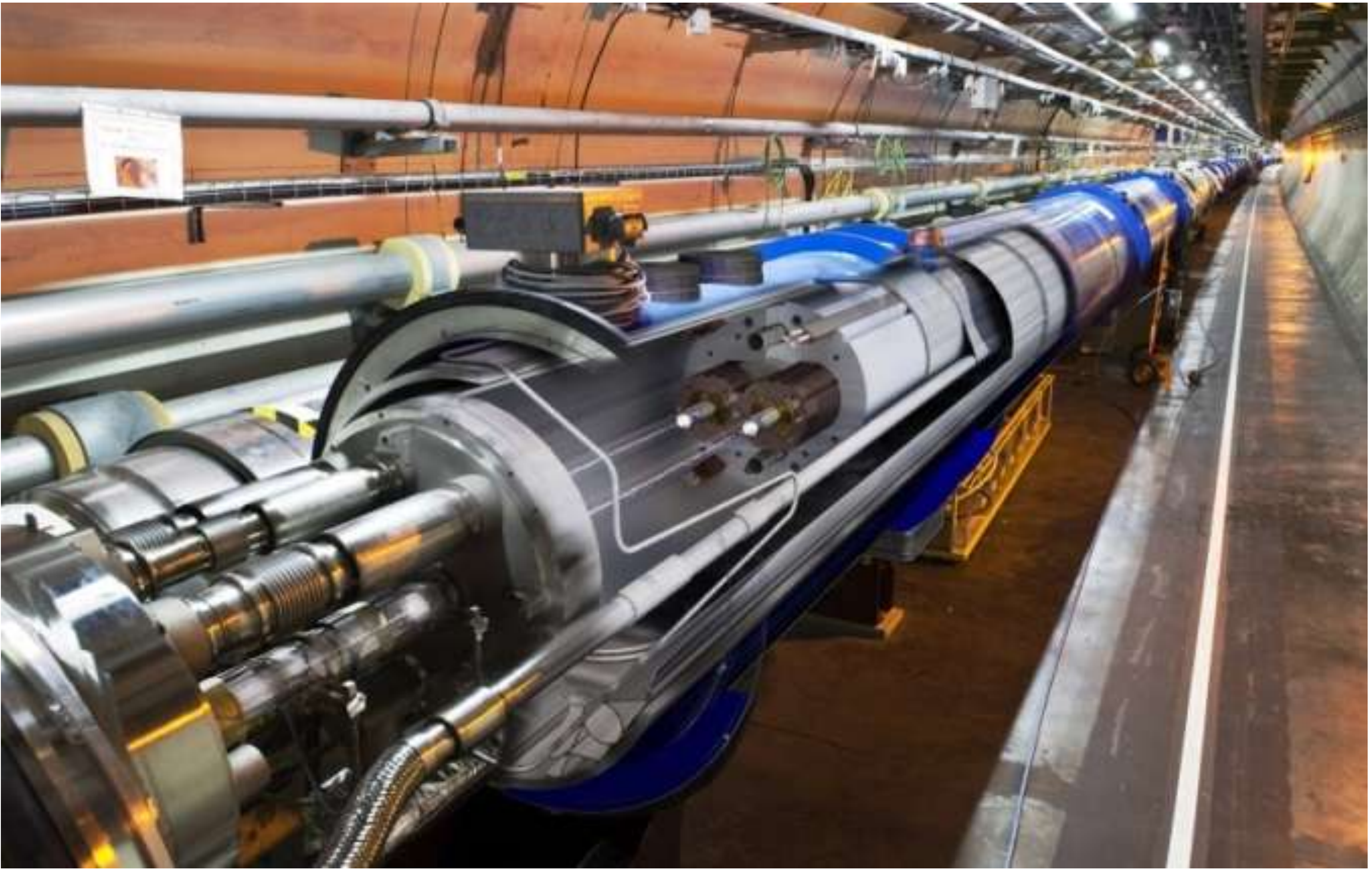
Common research project:
Siemens, IdaLab GmbH, TU Berlin

1-3% increase of annual energy

* ALICE = Autonomous Learning in Complex Environments

Example: Data analytic supports availability of systems – e.g. health check for CERN's Large Hadron Collider

SIEMENS
Ingenuity for life



99.9999991% the speed of light

The biggest detectors ever …

… 600 million collisions per sec

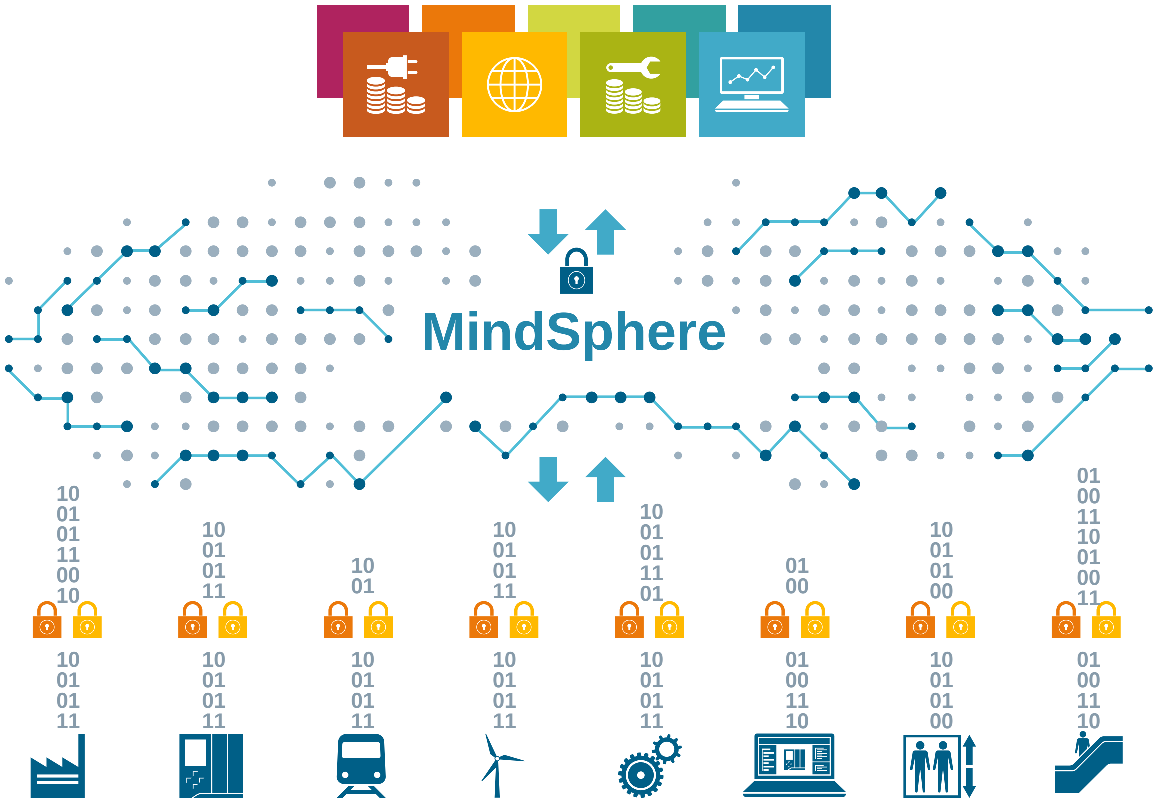
Huge supervisory system and hundreds SIMATIC systems controlling the production

With rule and pattern mining methods increase operating hours

Source: CERN

Siemens MindSphere – A Cloud-Based, Open IoT Operating System

SIEMENS
Ingenuity for life



MindApps

- Use **apps from Siemens, partners or develop own** apps
- Gain **asset transparency** and **analytical insights**
- Subscription based **pricing model**

MindSphere

- Open interface for development of **customer specific apps**
- **Various cloud infrastructures:** offered as public, private or on-premise

MindConnect

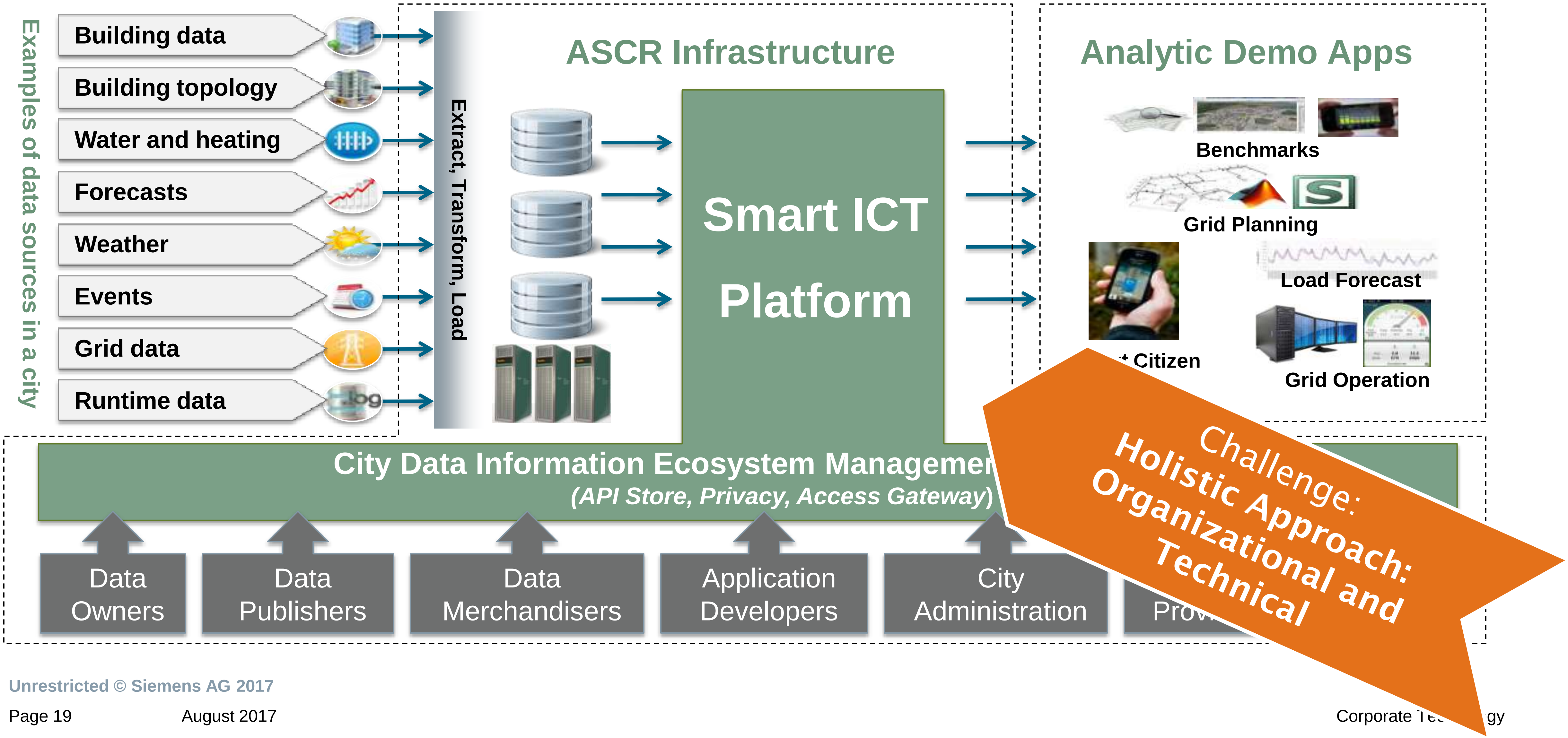
- **Open standards** for connectivity, e.g., OPC UA
- **Plug & play connection** of Siemens and 3rd party products
- **Secure** and **encrypted** data communication

Data analytics examples of Corporate Technology Research Group Configuration Technologies in Vienna

Source: Gerhard Engelbrecht, Urban Data Analytics in Vienna's Smart City Showcase Seestadt Aspern, April 2017

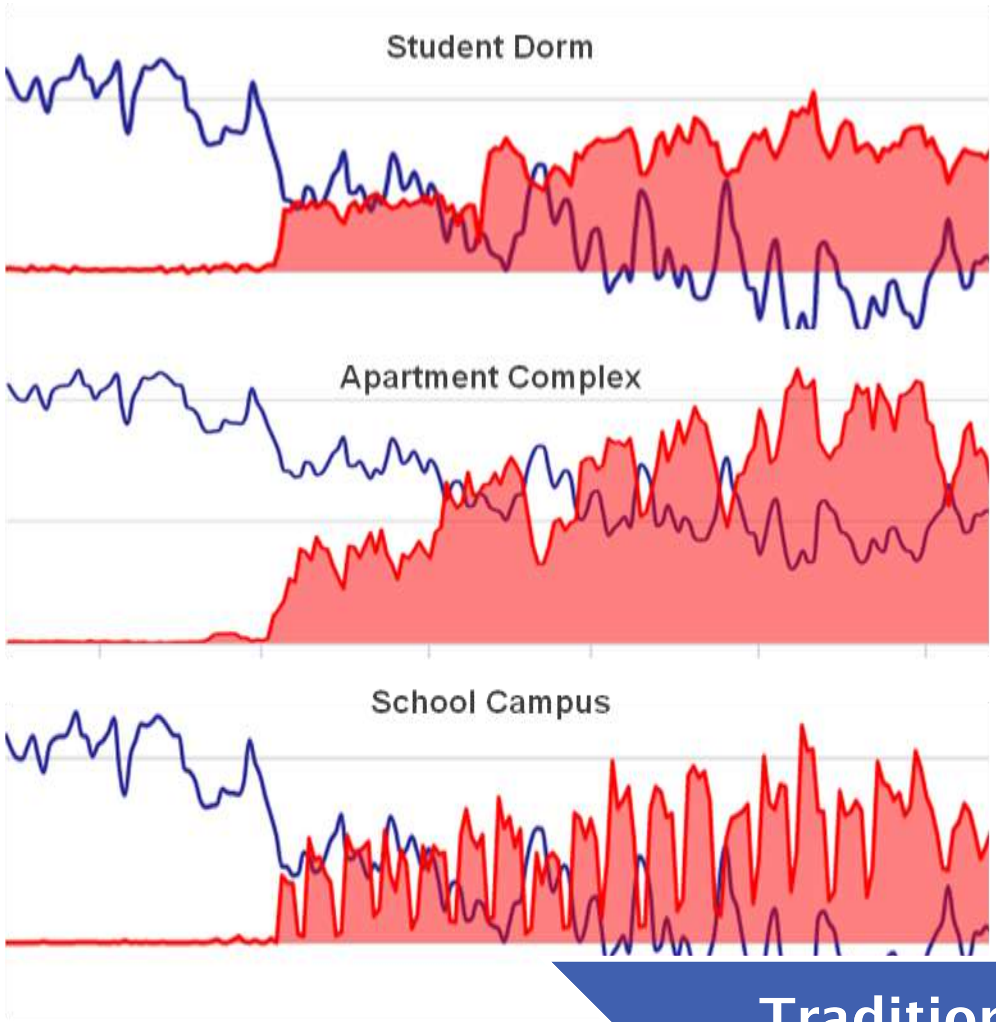
Smart City System Blueprint

SIEMENS
Ingenuity for life



Building Data Exploration using Navigator

SIEMENS
Ingenuity for life



Total Energy for Heating

- Start of heating period
- Dependency between outside temperature
- Weekend lowering

Benefit:
Detailed Data analysis

Energy consumption and generation

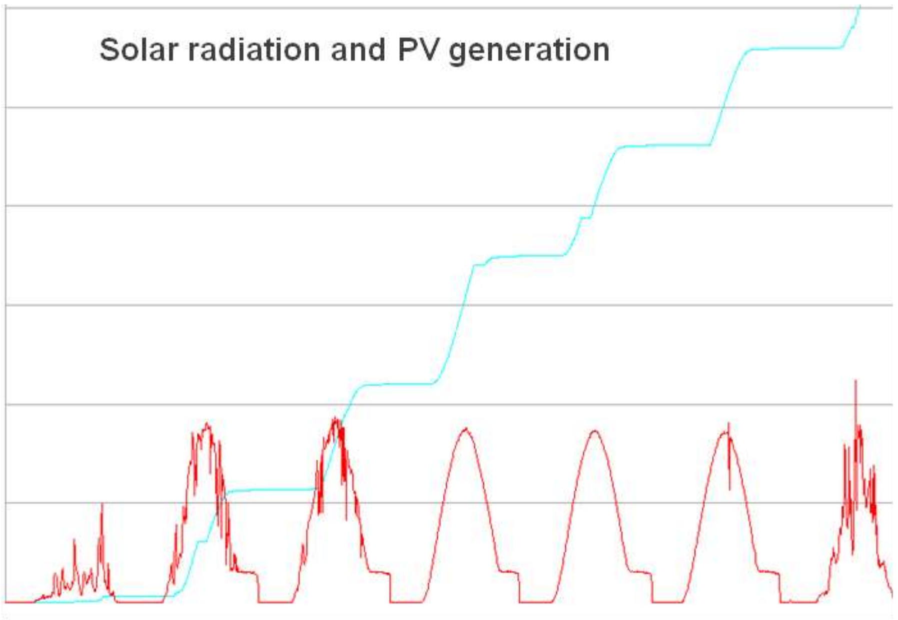
- Energy consumption stable
- ~70% is renewable energy

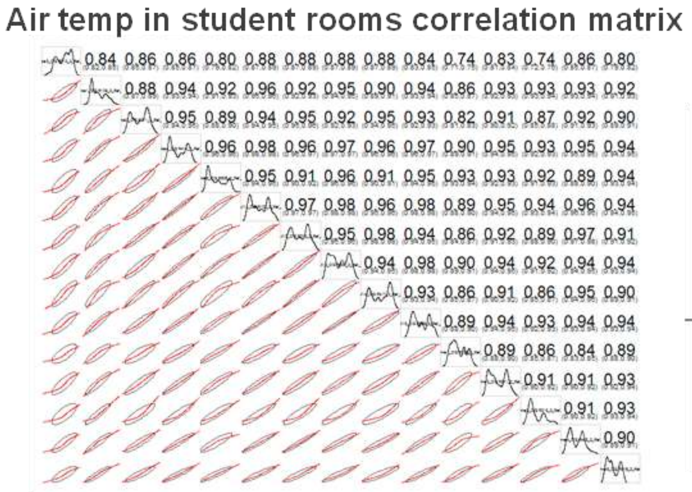
Traditional Business Intelligence
Structured and repeatable

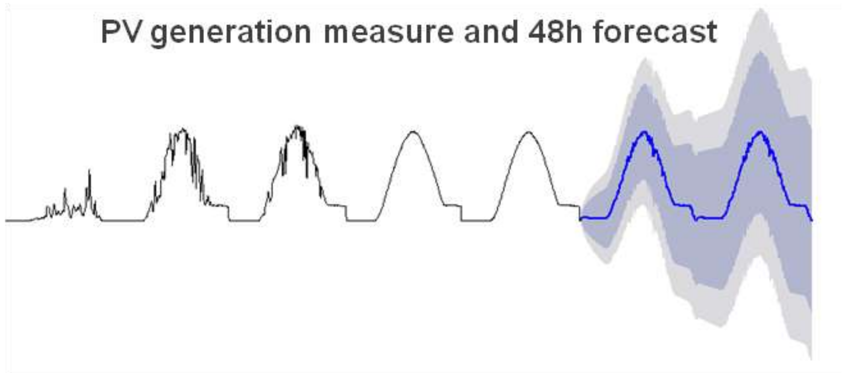
Data-driven Building Analysis

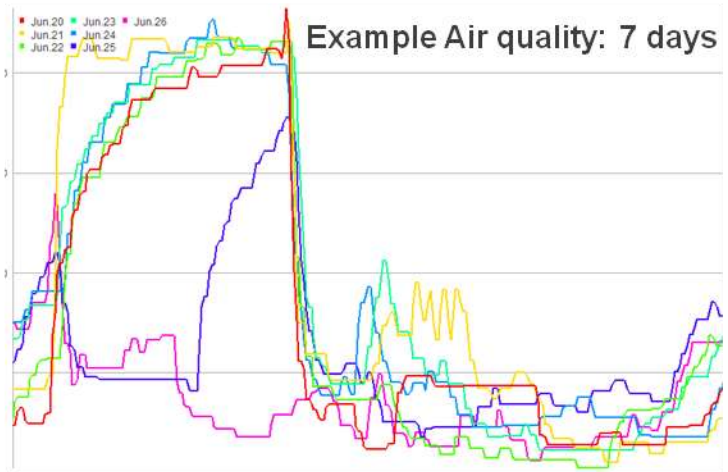
SIEMENS
Ingenuity for life

Business Intelligence & Data Discovery





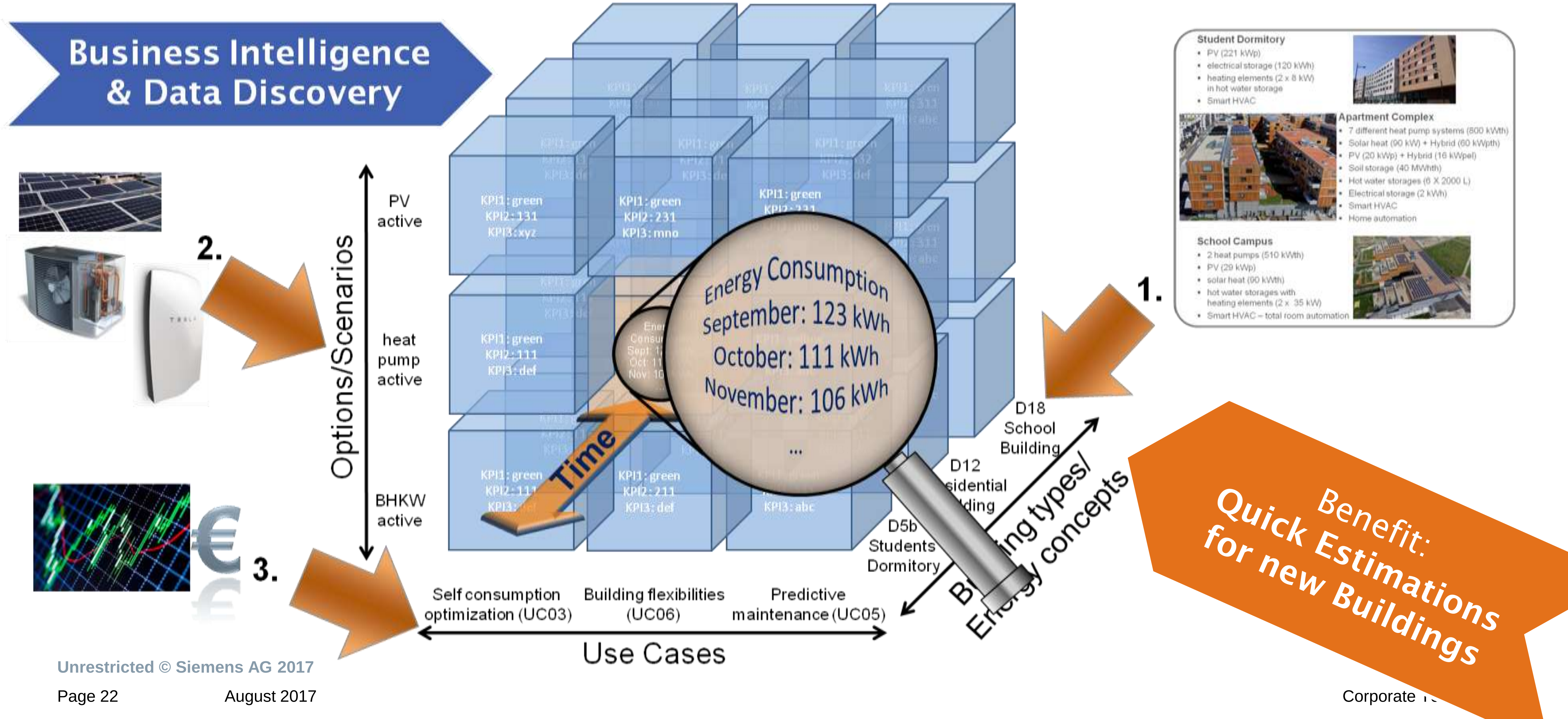




Benefit: Data analysis and operation verification

Data-driven Building Configuration

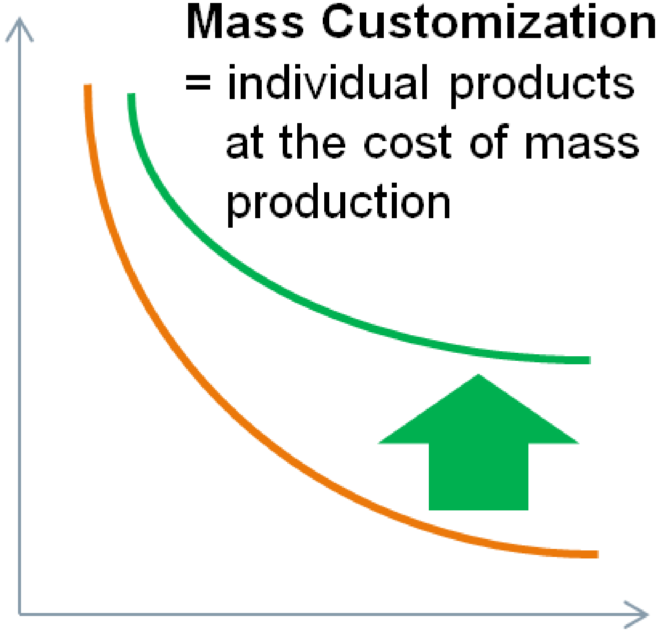
SIEMENS
Ingenuity for life



Product Configuration
at Corporate Technology Research Group
Configuration Technologies

Mass customization = mass production + customization

SIEMENS
Ingenuity for life



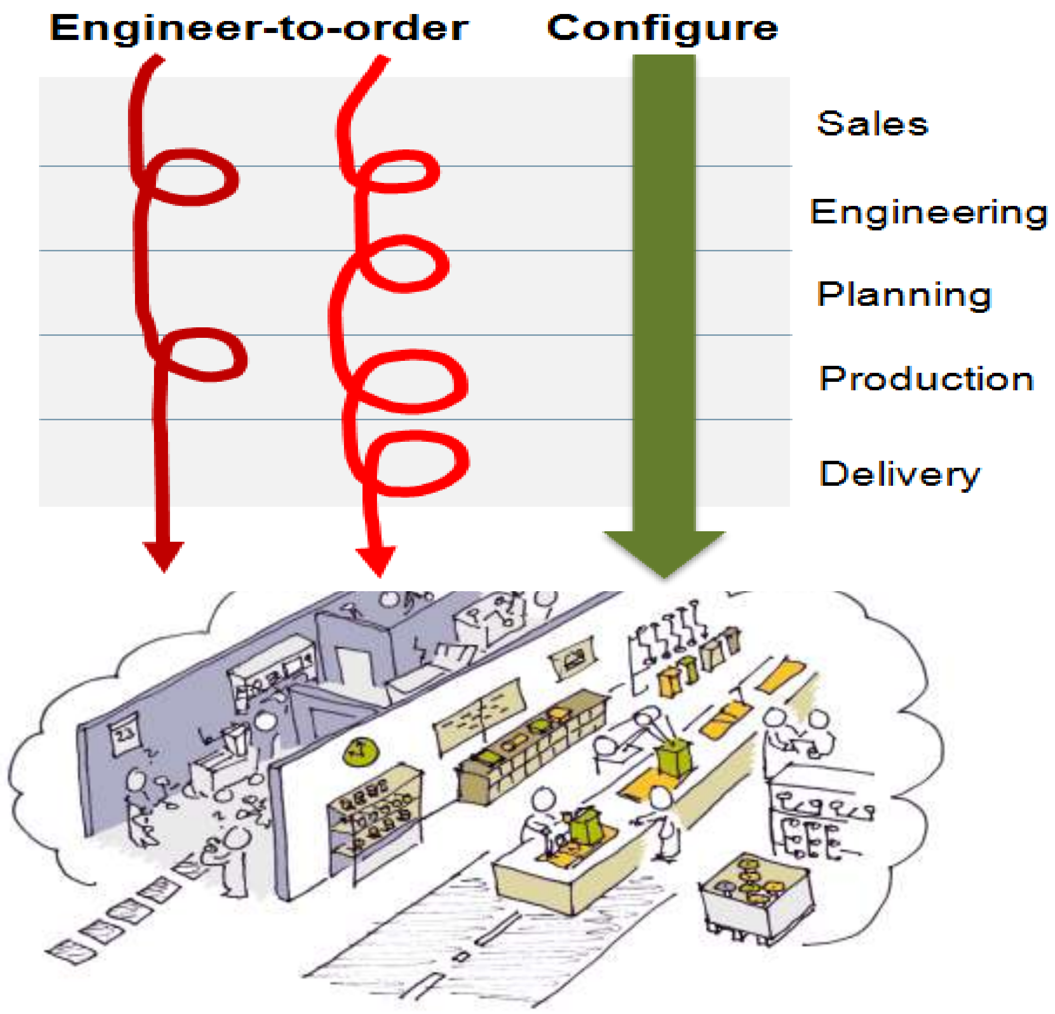
Production paradigms

- BTS = build-to-stock:
  product is built before final purchaser has been identified
- BTO = build-to-order:
  product is scheduled and built in response to a confirmed order

- PTO = pick-to-order:
  select variant or individual components without dependencies
- **CTO** = configure-to-order:
  dependencies between predefined components and their properties
- **ETO** = engineer-to-order:
  design some parts only after order (e.g. CAD drawing)

Benefits of configure-to-order vs. engineer-to-order

SIEMENS
Ingenuity for life



Increased **quality** of offers and orders

- Single point of truth
- Correct results are guaranteed

Reduced lead **time** / time to market

- Well defined products
- Smooth and integrated processes

Less **cost**

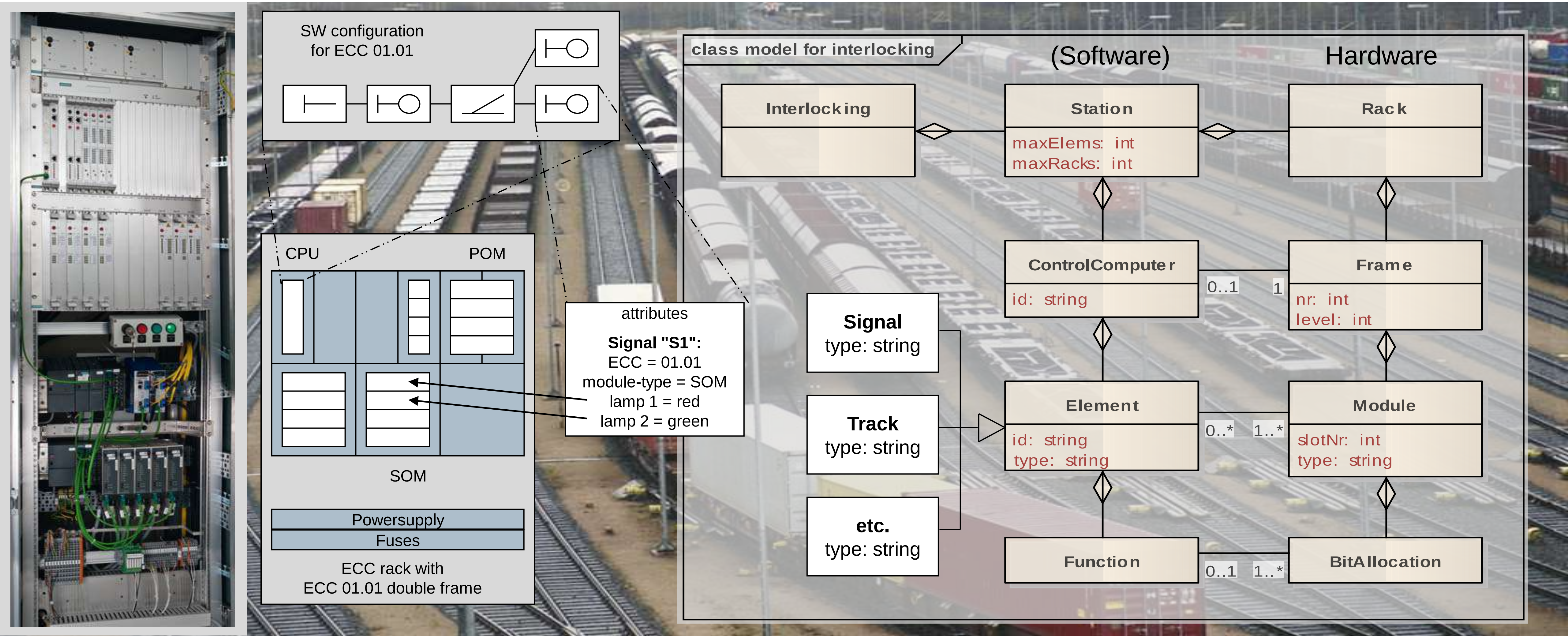
- Standardization and automation
- Reduced product complexity

Increased **customer** loyalty

- Less mass confusion
- Increased trust

Configuration of Railroad Interlockings

SIEMENS
Ingenuity for life



Artificial Intelligence – Railway Interlocking Configurators

SIEMENS
Ingenuity for life

Challenge

Multiple possible configurations (>10^{90}) and complex constraints of railway control equipment

Solution

Deductive logic (e.g. generative constraint satisfaction) for determining configurations, optimization to find the best configuration

Outcome

Configurators secure correct interlockings and highest level of train control

The Power of SAT Solvers

From: Sabharwal, IBM Watson Research Center, 2011

- SAT encoding for bounded model checking problem from SATLIB

```
p cnf 51639 368352
-1 7 0
-1 6 0
-1 5 0
-1 -4 0
-1 3 0
-1 2 0
-1 -8 0
-9 15 0
-9 14 0
-9 13 0
-9 -12 0
-9 11 0
-9 10 0
-9 -16 0
-17 23 0
-17 22 0
```

i.e., $((\text{not } x_1) \text{ or } x_7)$
$((\text{not } x_1) \text{ or } x_6)$
etc.

x_1, x_2, x_3, etc. are our Boolean variables (to be set to True or False)

Should x_1 be set to False??

The Power of SAT Solvers

- 10 pages later:

185 −9 0
185 −1 0
177 169 161 153 145 137 129 121 113 105 97
89 81 73 65 57 49 41
33 25 17 9 1 −185 0
186 −187 0
186 −188 0
...

i.e., (x_{177} or x_{169} or x_{161} or x_{153} …
x_{33} or x_{25} or x_{17} or x_9 or x_1 or (not x_{185}))

clauses / constraints are getting more interesting…

Note x_1 …

The Power of SAT Solvers

SIEMENS
Ingenuity for life

- Finally, 15.000 pages later

```
−7 260 0
7 −260 0
1072 1070 0
−15 −14 −13 −12 −11 −10 0
−15 −14 −13 −12 −11 10 0
−15 −14 −13 −12 11 −10 0
−15 −14 −13 −12 11 10 0
−7 −6 −5 −4 −3 −2 0
−7 −6 −5 −4 −3 2 0
−7 −6 −5 −4 3 −2 0
−7 −6 −5 −4 3 2 0
185 0
```

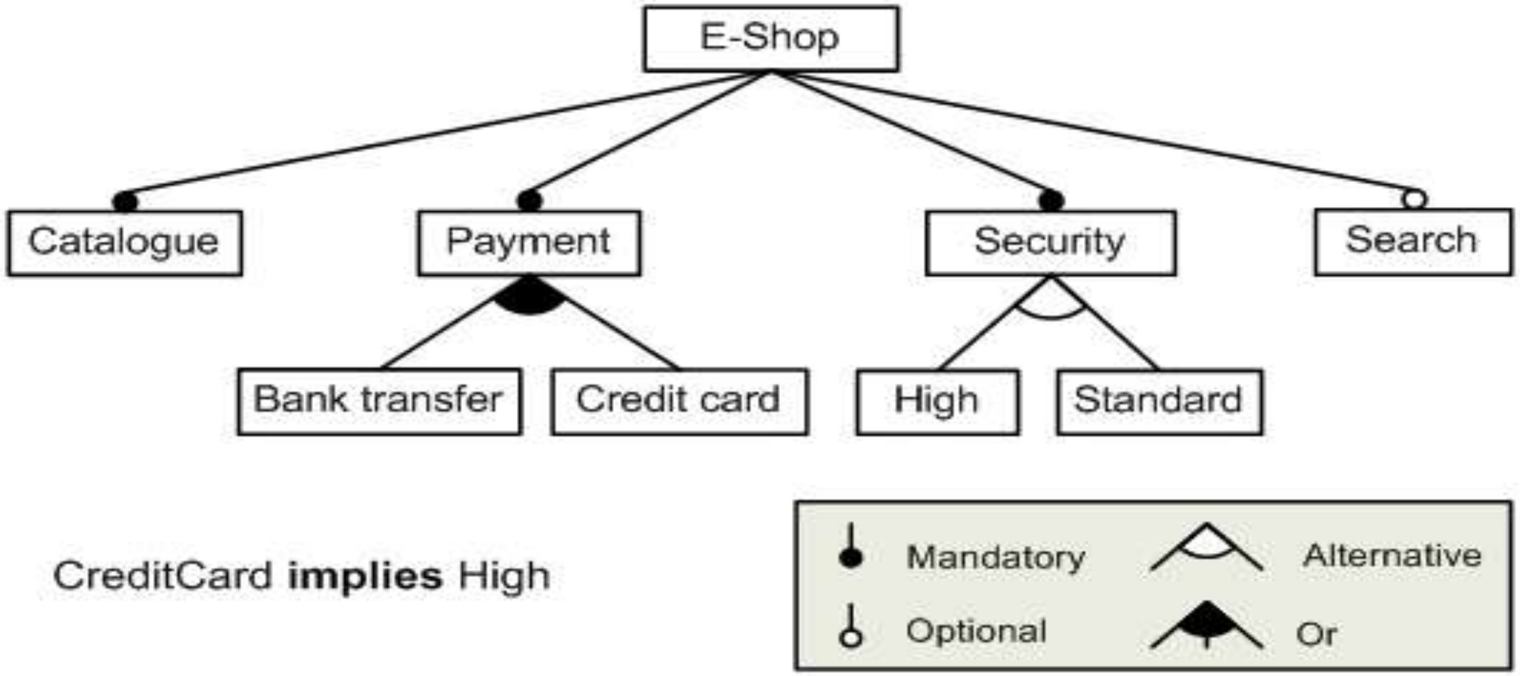
Search space of truth assignments: $2^{50000} \approx 3.160699437 \cdot 10^{15051}$

Current SAT solvers solve this instance in just a few seconds!

Feature Modelling

SIEMENS
Ingenuity for life

- Simple, tree-like representation of a product family
- Cross-tree constraints (requires = implies, excludes = incompatible)
- Often used in product line engineering (PLE) for variability modeling
- Metrics of model properties
  - Complexity
  - Dead features



Source: http://en.wikipedia.org/wiki/Feature_model

Exercise:
Feature Modeling of hardware modules

SIEMENS
Ingenuity for life

Configuration problem:

- A hardware rack has 4 slots (A, B, C, D) where modules can be mounted (at most one in each slot)
- There are 3 modules (1, 2, 3) which must be mounted on exactly one slot
- Module 2 is double-sized and occupies the next slot, too (A->B, B->C, C->D)

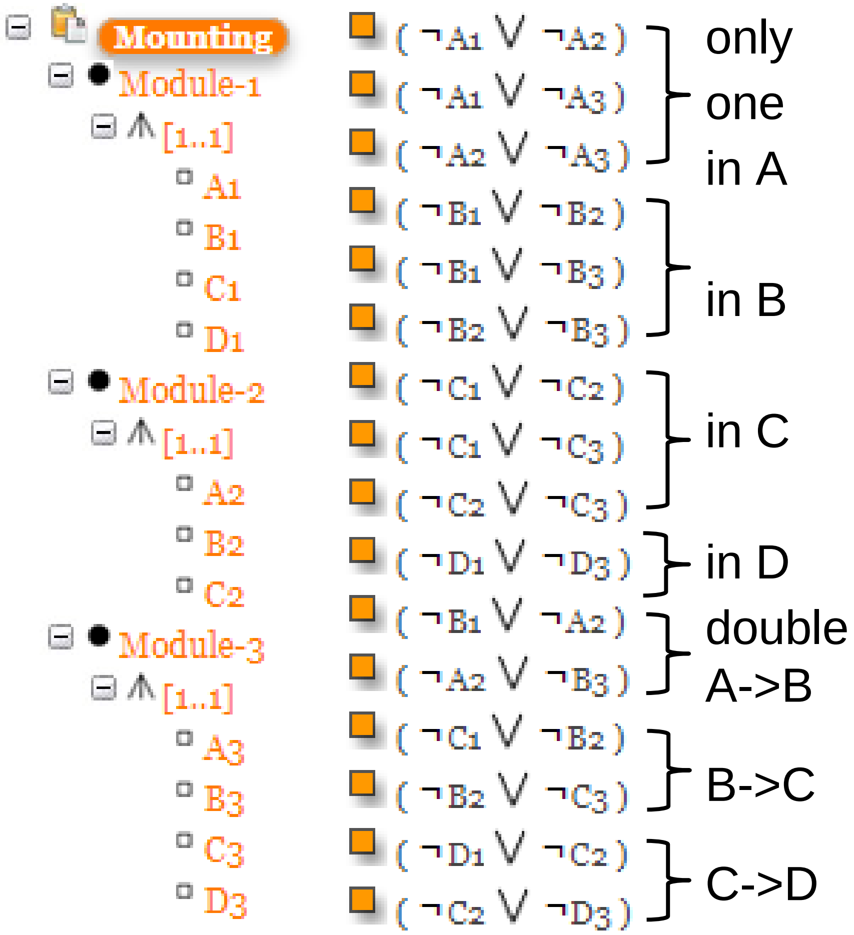
Model this in http://www.splot-research.org/:

- Open "Feature Model Editor"
- "Create a New Model"
- Edit "Feature Diagram"
  - what are mandatory features? what alternatives?
- Add the necessary "Cross-Tree Constraints"
- "Run analysis"
  - how many valid configurations?
- Click "Configure" to test
  - You need **not** "Save to Repository"

See example solution "SlotsForModules" in repository

6 solutions:

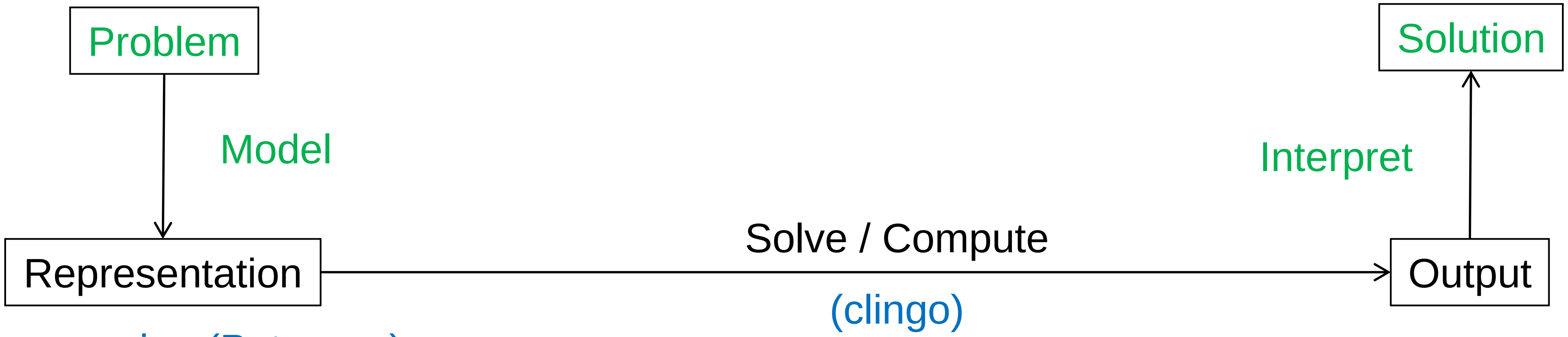
- A1,B2,D3
- A1,B3,C2
- A2,C1,D3
- A2,C3,D1
- A3,B1,C2
- A3,B2,D1



Declarative Problem Solving

Algorithm = Logic + Control (Kowalski, 1979, CACM):

- What is the problem? Clear specification!
- How to solve? Powerful generic solver(s)!



- Answer Set Programming (Potassco)

Constraint Satisfaction Problem (CSP)

A **CSP** is a triple <V, D, C>:
- V is a finite set (or sequence) of variables $V_1, V_2, \ldots, V_n$
- D is the corresponding set of domains D_i of values
- C is a finite set of constraints $C_1, C_2, \ldots, C_m$

Each **constraint** $C_j(V_k, \ldots, V_l)$ limits the values of the vars
- unary, binary, non-binary (arity>2), global constraints
- defined intensionally by a formula (possibly infinite)
- or extensionally by a list of allowed combinations

A **solution** is a valid instantiation (model), i.e. an
- assignment of values to all variables such that no constraint is violated
- the CSP is satisfiable if at least one solutions exits

Tools: Choco, Gecode, JaCoP, Minion, MiniZinc, etc.

Constraints are undirected, logical expressions describing conditions for correctness of a solution to a configuration problem (declarative)
- *e.g.: 2 * A = B (the value of variable B is the double of A)*

and can be used for **multiple purposes**:
- Checking consistency (if A and B are both set)
- Filtering out invalid or impossible options (e.g. if A=3, B can only be 6)
- Repairing inconsistencies or completing configurations in any direction (e.g. if A is set then set B correctly, or if B is set then set A correctly)
- Explaining what is inconsistent and how it can be repaired

Solvers use heuristics to speed-up search

SIEMENS
Ingenuity for life

Search steps (exploration) alternate with deterministic constraint propagation (exploitation)

Constraint propagation

- is used to filter out as many inconsistent assignments as possible
- this does not restrict the found solution(s)
- for small problems, pre-compile alternatives completely, e.g. BDD or MDD
- otherwise use K-consistency
  - practically, only arc-consistency is sufficiently performing (cubic complexity)
  - stronger consistency is too expensive
- it cannot filter away all inconsistent values
- for that, search needed
- what are good search strategies?
  - backtracking? complete?
  - local search? hill-climbing?

Heuristics for search

Minimal remaining values (MRV):

- choose the variables with fewest allowed values

Largest degree (DEG):

- then select the variable that is involved in the largest number of constraints on other unassigned variables

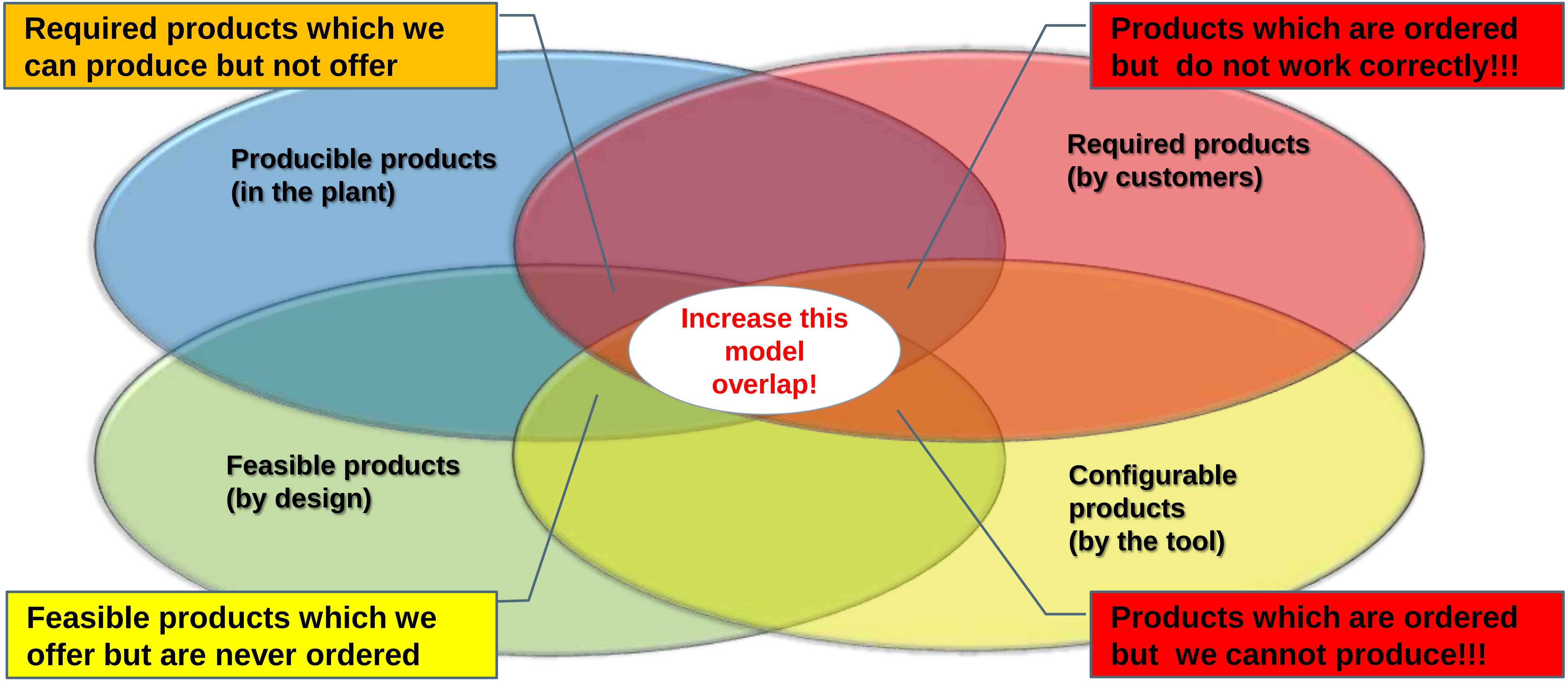
Least constraining value (LCV):

- given a variable, choose least constraining value
- i.e. the one that leaves the maximum flexibility for subsequent variable assignments

Decomposition into independent sub-problems:

- if possible

Improve the quality of product models



How to deal with an arbitrary number of variables

Problem: How to handle optional values (e.g. in an arbitrary-sized set)
Solution: Dynamically set variables active

Conditional CSP (originally called Dynamic CSP) = $\langle V, V_i, C_C, C_A \rangle$

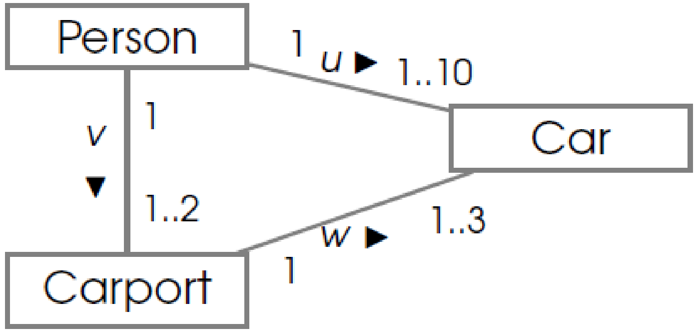
- V are the variables (with a given domain)
- V_i are the variables initially active (subset of V)
- C_C are compatibility constraints like in CSP
  but only active when all their variables are
- C_A are **activation constraints** which activate/deactivate variables
- Solution: All active variables are assigned a valid value

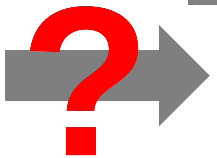
It was shown that Conditional CSP are equally expressive as CSP

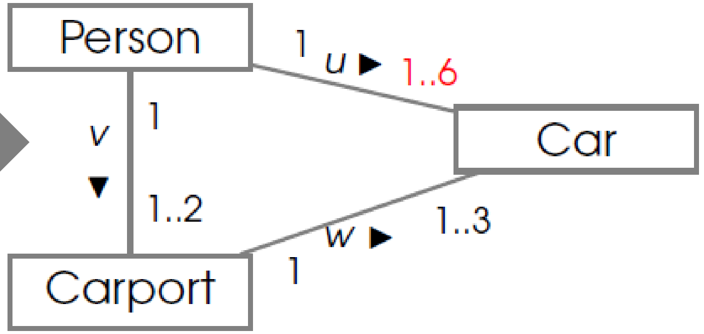
- Polynomial transformation: map activation constraints to newly created Boolean variables containing the activation information (one for each original variable)

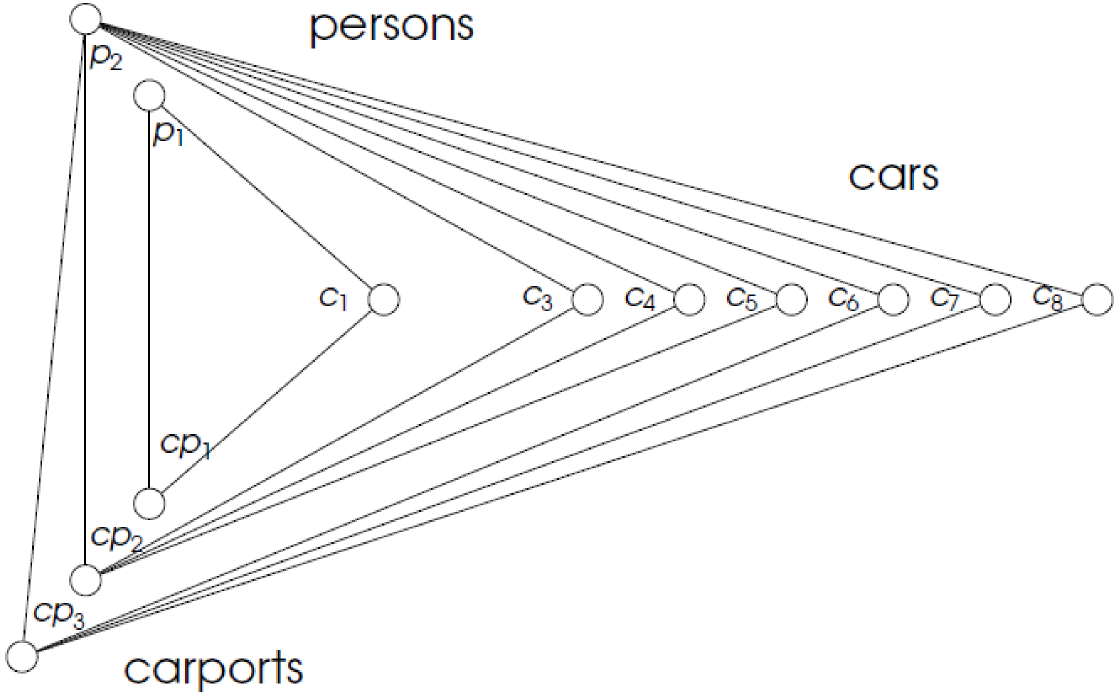
Find upper bounds to increase solving performance

from Habilitation talk of Feinerer, 2014







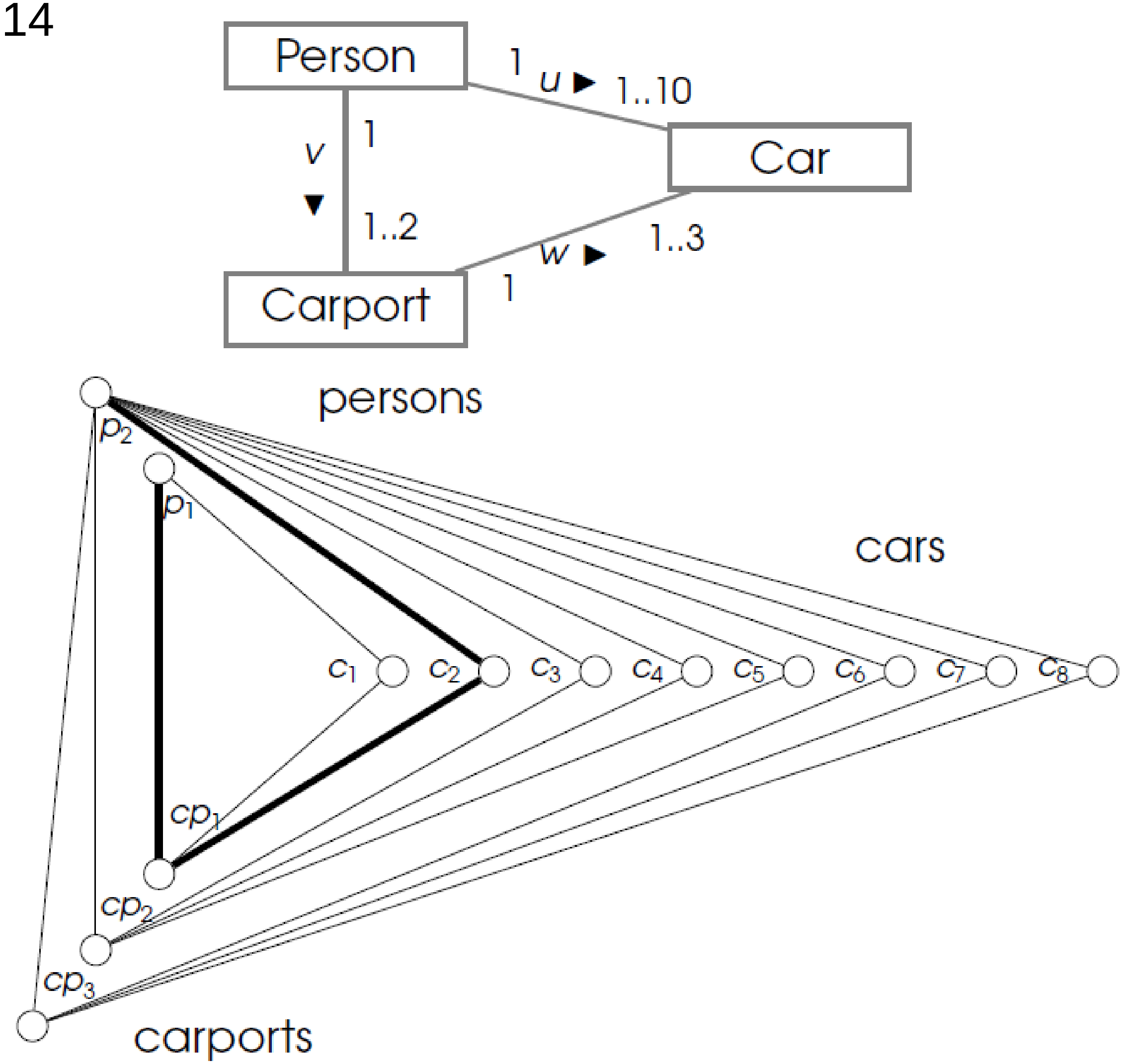


Be aware of pitfalls!

SIEMENS
Ingenuity for life

from Habilitation talk of Feinerer, 2014

Missing constraint: u = v + w



Linking Configuration Technologies and Data Analytics

Combining configuration knowledge with runtime data analytics enables better and faster results in product engineering & diagnosis

SIEMENS
Ingenuity for life