# How new technologies increase engineering complexity and what to do about it…

Key Note Address at SCIFI-IT'2022

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SCIFI-IT

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## Today's Key Note Address

*What I want to share with you…*

Let's get started…

## How new technologies increase engineering complexity and what to do about it...

- Looking at novel technologies that step-by-step are coming into our lives, we can be impressed by the results, by the possibilities new products offer, and by the way they slowly change our lives as well.
- These networked technologies are often communicating continuously with other systems and have a certain degree of autonomy for taking decisions. Such “Cyber Physical Systems” (CPS), with sometimes the human in the loop, pose real challenges to industries.
- Looking from a systems design point of view, such new technologies tend to increase the complexity a designer or an engineer needs to manage. Characterised by multiplicity, by interdependence, by a certain degree of heterogeneity, with continuous interactions, and overall with a product or system behaviour that is difficult to predict, such systems, such systems are also difficult to validate. And, if it concerns safety-critical embedded systems, to get those systems certified.
- Still, this is a road that is taken, and when looking for example at autonomous vehicles of autonomous drones, such technologies are being considered, so to be able to cover the stakeholder requirements, or more in general the expectations from our society.
- So, what to do about them… This presentation aims at analysing the challenges and to propose a methodology to support the design process. Starting from a new value-based approach to system design and engineering, research directions are suggested for the coming years, so to be able to prepare the future.



## In short

- Novel (networked and intelligent) technologies
- Complexity
- Model-Based Systems Engineering and how to use it
- How to ensure we are developing the right system…
  … and how to develop it right?

## Our society is changing rapidly

*and new connected devices play a major role…*

Let's just look back a few years and see what happened

## So, what am I referring to…

1980's

2000's

"Local optimisation" or "Reuse" would not have led to these new products…

How to allow creativity?
How to look at other concepts?

Pictures taken from internet

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# But also…


"Local optimisation" or "Reuse" would not have led to these new products…

How to allow creativity?
How to look at other concepts?

Pictures taken from internet

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# And of course…


"Local optimisation" or "Reuse" would not have led to these new products…

How to allow creativity?
How to look at other concepts?

Pictures taken from internet

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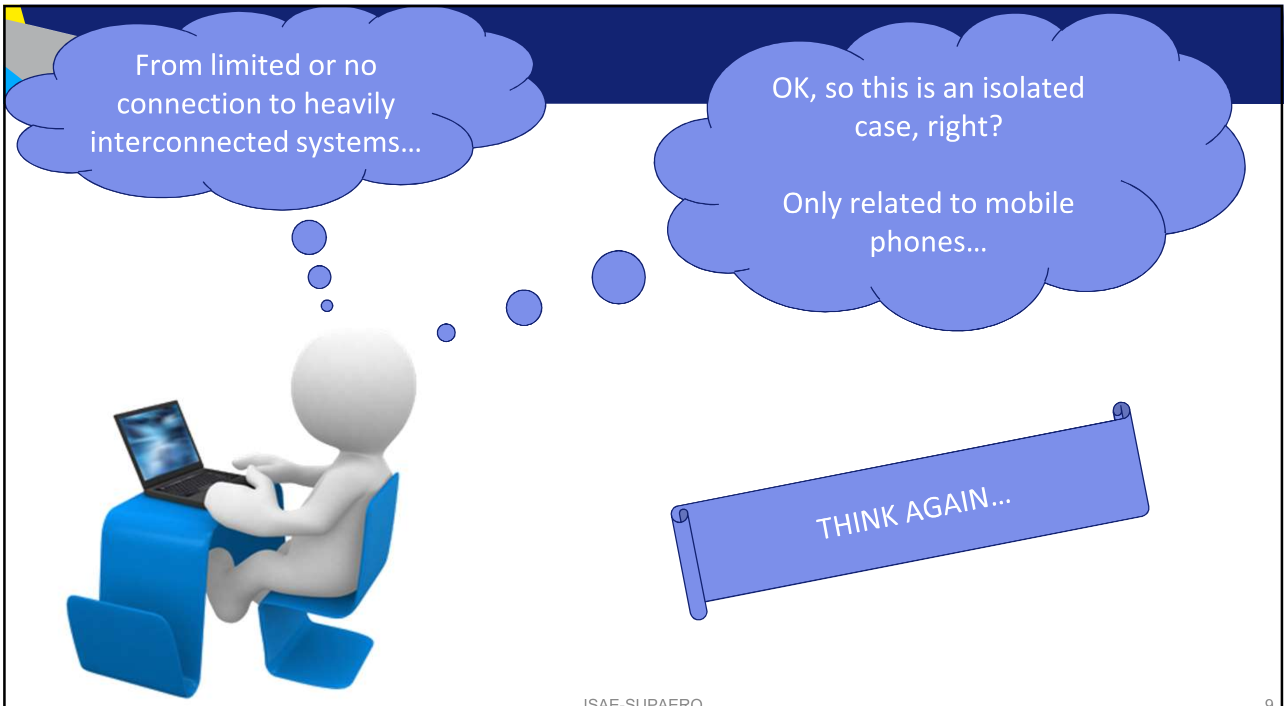
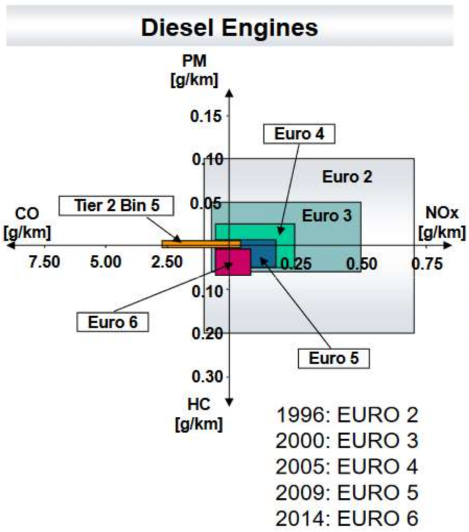
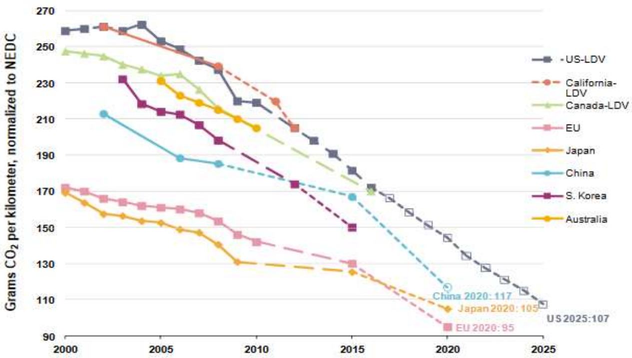





# Let's look at another example



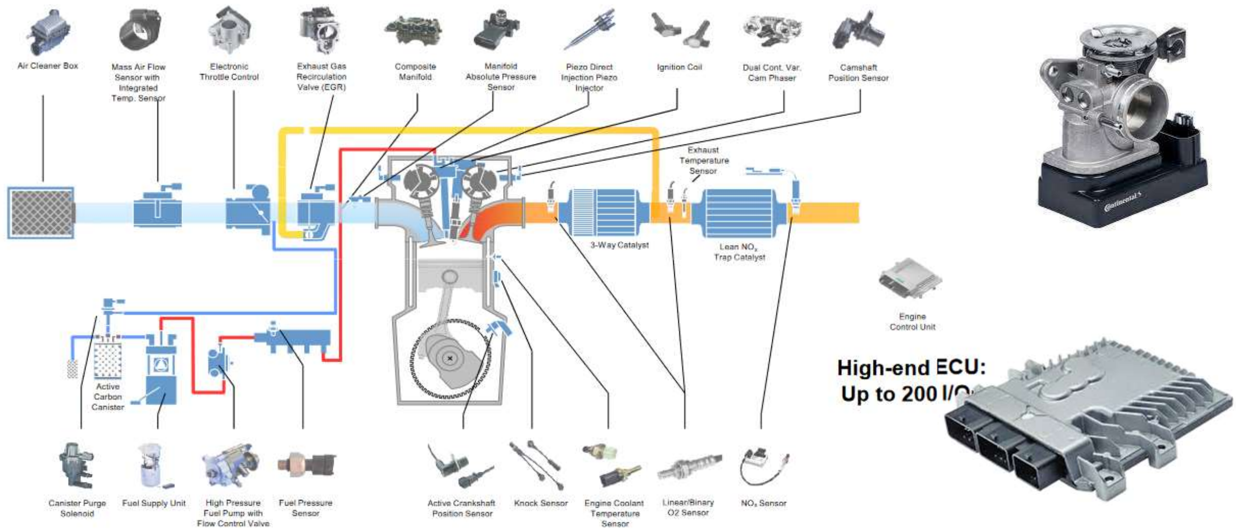




The only way to address these challenges was via specific engine management systems including different sensors, actuators, and ECU(s)

Sources: European Commission, EPA

D. Claraz, "Automotive SW Architecture – Engine Management Systems", Ecole d'Ete 2013.

# Gasoline engine management to manage the combustion and the depollution




D. Claraz, "Automotive SW Architecture – Engine Management Systems", Ecole d'Ete 2013.

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Images Continental, from internet

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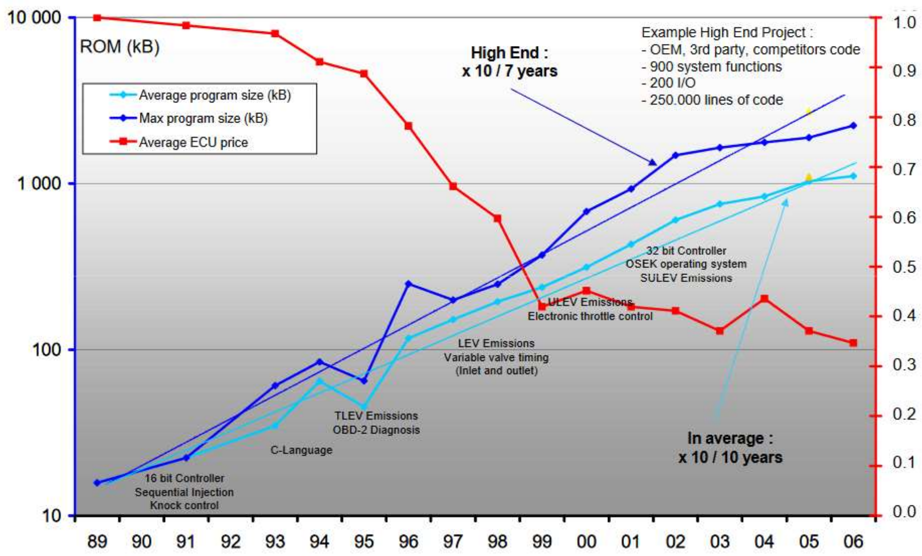
# Cost pressure on mass-volume production pushes for lower-end processors…




D. Claraz, "Automotive SW Architecture – Engine Management Systems", Ecole d'Ete 2013.

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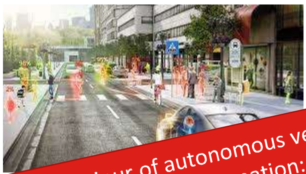
# New technologies appear also in infotainment…

- Linking other devices for telephoning, music and video
- Using telephone applications directly via the car
- Very extended personalisation of the vehicle cockpit
- …

Images Continental, from internet



# Growing into autonomous vehicles…



Cars continuously connected to the rest of the world, communicating autonomously with other systems and having a certain degree of autonomy for taking decisions.

The behaviour of autonomous vehicles is induced by the not-mastered information: the developer(s) of the vehicle (sub-systems) has no control on the information that the vehicle will receive, but which information is used in the reasoning process on board of these vehicles and the applied decisions ➔ This can lead to unpredictable (emergent) behavior.

- autonomously driving vehicles, exchanging information with each other and with the outside world,
- search for the optimal routes (distance, time …),
- getting up-to-date (local) weather and traffic information, etc.
- decision on route over another one depending on the received information,
- detection of (moving) obstacles and effectuating corrective actions
- …

Motus, L, Vingerhoeds, R.A., Meriste, M., «Challenges for Real-Time Systems Engineering, Part 1: State-of-the-Art», Proceedings of the Estonian Academy of Sciences and Engineering, Vol. 11, Nr. 1, pp. 3-17, 2005.
Motus, L, Vingerhoeds, R.A., Meriste, M., «Challenges for Real-Time Systems Engineering, Part 2: Towards Time-Aware Technology», Proceedings of the Estonian Academy of Sciences and Engineering, Vol. 11, Nr. 1, pp. 18-30, 2005.

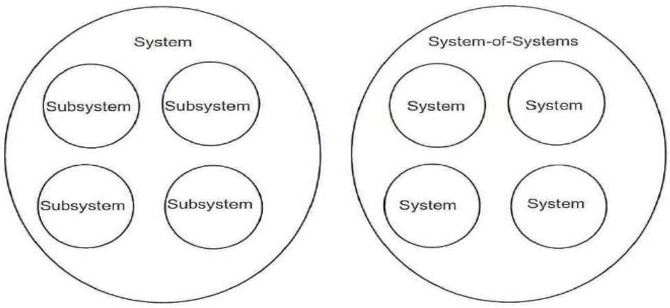
Images Continental, from internet

# System of Systems (SoS)

- A system of interest consisting of different system elements in their own right is called a system-of-systems (SOS)
  - similar architecture to that of a system
  - managerially and operationally independent
  - potentially at different location geographically
    ➔ access to different information and in different contexts

- Individual elements of SOS are optimised for their own purpose

- Resulting SOS therefore most likely not optimised






# Internet of Things (IoT) …

- Connecting any device to the Internet (and/or to each other)
  - cellphones, coffee makers, washing machines, headphones, lamps, wearable devices …
- Interrelated computing devices, mechanical and digital machines, objects, animals or people with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction
- Giant network of connected "things" (which also includes people). The relationship will be between people-people, people-things, and things-things.

➡ **Now it is getting complex…**

## The impacts are tremendous

*and go beyond just the system under development…*

What do we need to do to address these issues

## Complex systems are systems that display behaviour that is unexpected, emerging, and/or unpredictable.

- Large scale applications, distributed, with many participants, multiple interests, multiple perspectives,
- The involvement of many stakeholders with different, sometimes conflicting, interests and goals, requiring extensive cooperation and coordination throughout the system's lifecycle,
- Decision-making by stakeholders on the basis of uncertain, incomplete, inconsistent, or ambiguous information,
- Continuous change that may span many years,
- Systems of systems – embedded and connected – autonomous sub-systems with different norms and values, rules of engagement and agreement, communication architectures, and requirements for trust,
- Many parts and many dependencies between parts and with the environment,
- Technology not readily available at the beginning of the program,
- Not one unique objective measure to determine the quality of a design,
- Emergent behavior, unexpected events

Well, isn't this exactly what we are talking about?

Extended from
Flood, R. L., (1990). "Liberating Systems Theory", In: Liberating Systems Theory. Contemporary Systems Thinking. Springer, Boston, MA., and Poel I. (2009). "Values in engineering design". In: Meijers A, editor. Handbook of the Philosophy of Science. Volume 9: Philosophy of technology and engineering sciences. Amsterdam: Elsevier, pp. 973–1006.

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## Modern complex systems and what characterizes them…

- Systems of systems (with the associated characteristics)
- Reuse of previously developed systems and software ← Carefull!
- Integration becomes a major issue ←
- Careful, the problems often emerge at interfaces between (sub-) systems and/or with the outside world
- Need for completes solutions along logical and time-wise coherence and consistency

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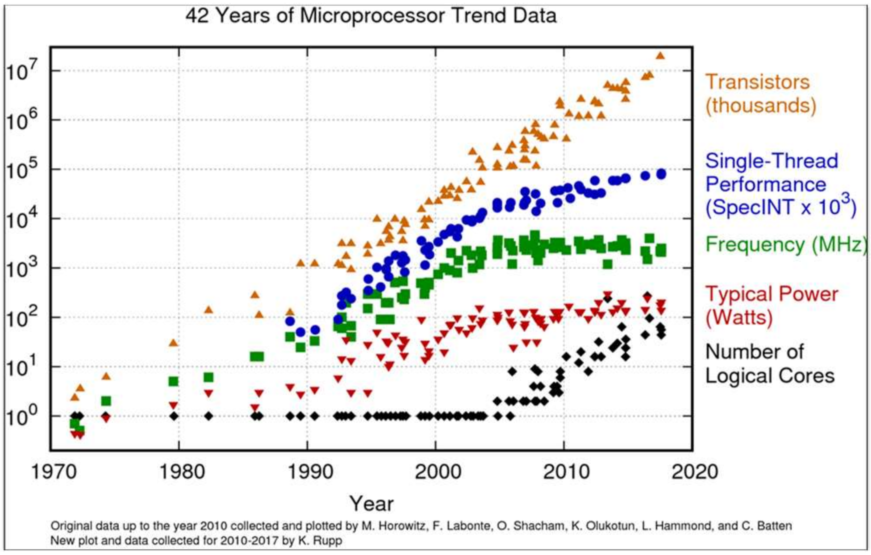
## The tendency is not about the stop…




K. Rupp, "42 Years of Microprocessor Trend Data". https://www.karlrupp.net/2018/02/42-years-of-microprocessor-trend-data/ (accessed Jun. 11, 2019).

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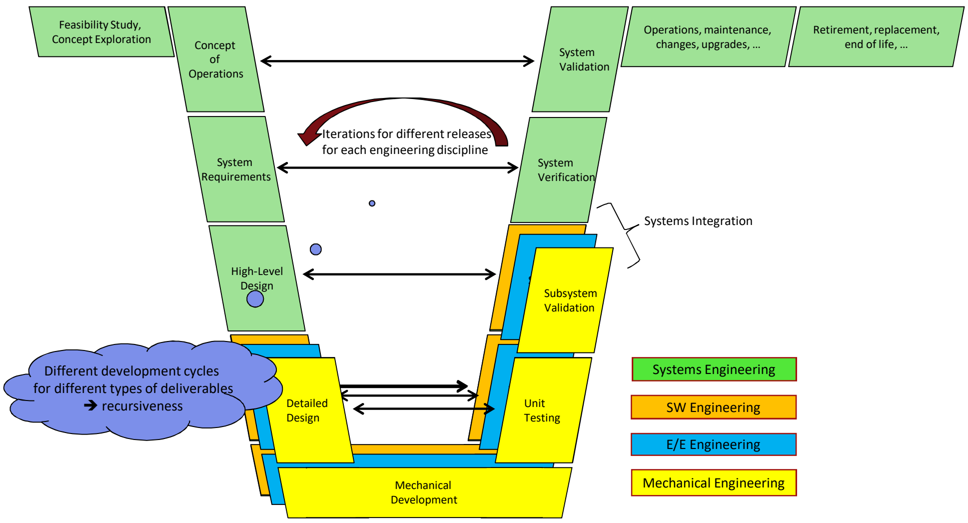
## First of all, let's look at the design processes

*and how to address needs and desires…*

Even the design process is getting complex

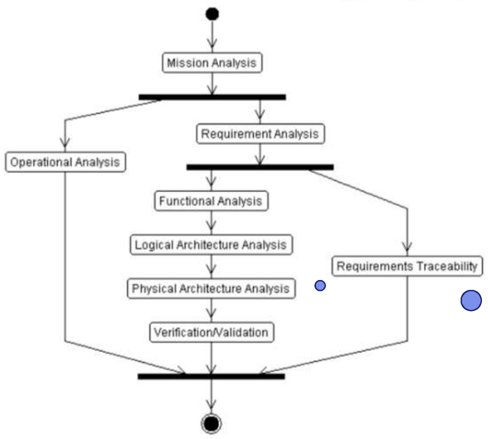
## Classical view on systems development




Vingerhoeds, R., Mifdaoui, A., Saqui-Sannes, "Educational challenges for Cyber-Physical Systems Modelling", Proceedings MOSIM'18, pp. 221-228, Toulouse, 27-29 June 2018.

# Concept phase

Needs & Desires
Requirements
Functional Analysis
Logical Architecture
Physical Architecture



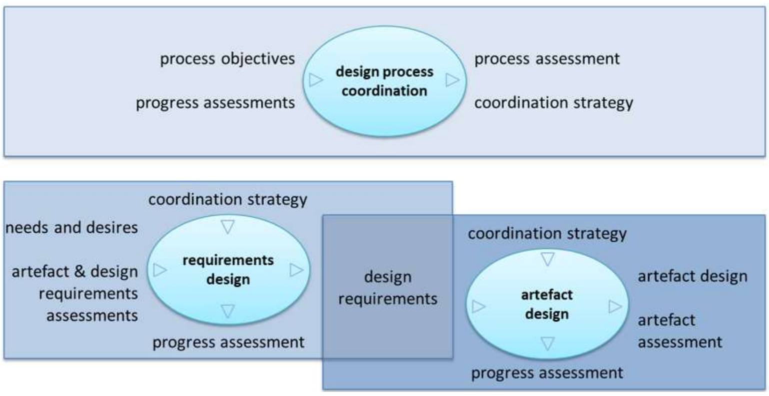

Use of Model-Based Systems Engineering as main paradigm

Razafimahazo E., P. de Saqui-Sannes, R.A. Vingerhoeds, J. Soula, R. Mège, C. Baron, "Towards a Customizable Architecture for Indoor Multi-Usages Drones", accepter for ICAS 2022.



# Three main processes in parallel

- Adapt and refine initial requirements ➔ requirements design
- Integrated design of artefact/system (taking different perspectives into account) ➔ artefact design
- Coordinate design process (e.g. resource management) ➔ design process coordination
- With simulation / experimentation getting to the revised generic design model




Brazier, F., Langen, P. van, Lukosch, S., Vingerhoeds, R. «Design and Engineering of Complex Systems», in: H.L.M. Bakker and J.P. Kleynen editors «Projects and People – Mastering Success», pp. 34-59, NAP Foundation Press, 2018.

## Now we can start to elaborate

- **Functional requirements** will drive the functional assessment for the design and will lead to a logical architecture
- **Behavioural requirements** will drive the performance and will be used to verify whether the proposed solutions are performant enough
- **Structural requirements** will impose (partial) solutions and constraints and therewith limit the design space
- **Experiential considerations** influence the design and its process, and may partly be transformed into funtional, behavioural and/or structural requirements

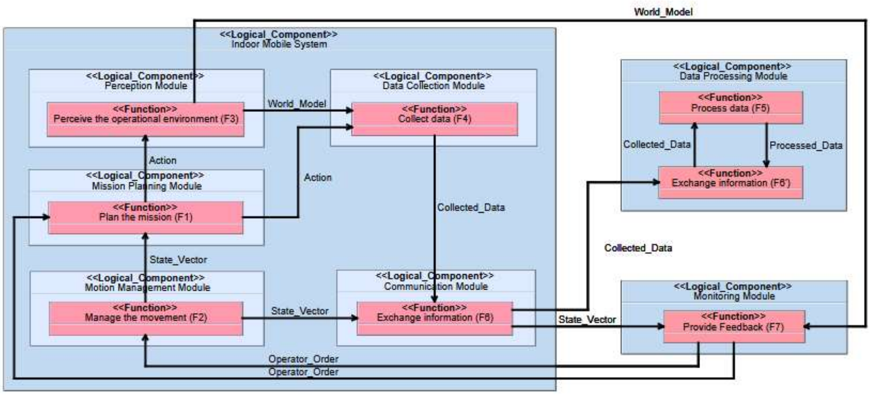
| ID | System requirement | Type (FBSE) | Priority | UC 01 | UC 02 | UC 03 | UC 04 | Trace to stakeholder needs | Trace to Functions | Stakeholder(s) |
|---|---|---|---|---|---|---|---|---|---|---|
| Sys.R.01.04 | The system shall use the provided Building_Data when available. | Functional | Medium | x | x | x | x | Stk.Nd.01.04 | Process data | BIM_Expert |
| Sys.R.01.04.01 | The system shall be compatible with IFC files. | Structural | Medium | x | x | | | Stk.Nd.01.04 | | BIM_Expert |
| Sys.R.01.04.02 | The system shall read the provided Building_Data. | Functional | Medium | x | x | x | x | Stk.Nd.01.04 | Process data | BIM_Expert |
| Sys.R.01.04.03 | The system shall store the provided Building_Data into a memory. | Functional | Medium | x | x | x | x | Stk.Nd.01.04 | Process data | BIM_Expert |
| Sys.R.01.04.04 | The system shall be able to process the provided Building_Data. | Functional | Medium | x | x | x | x | Stk.Nd.01.04 | Process data | BIM_Expert |
| Sys.R.01.04.05 | The system shall be able to use the 2D plan of the Building. | Structural | Medium | x | x | x | x | Stk.Nd.01.04 | | BIM_Expert |
| Sys.R.01.04.06 | The system shall be able to use the BIM model of the Building. | Structural | Medium | x | x | x | x | Stk.Nd.01.04 | | BIM_Expert |
| Sys.R.01.05 | The system shall exchange information with the Operator. | Functional | High | x | x | x | x | Stk.Nd.01.05 | Exchange information | Operator |
| Sys.R.01.05.01 | The system shall receive the Orders from the Operator. | Functional | High | x | x | x | x | Stk.Nd.01.05 | Plan the mission & Provide Feedback | Operator |
| Sys.R.01.05.02 | The system shall receive the provided Building_Data from the Operator. | Functional | Medium | x | x | x | x | Stk.Nd.01.05 | Exchange information | Operator |
| Sys.R.01.05.03 | The system shall provide the collected Building_Data to the Operator. | Functional | High | x | x | x | x | Stk.Nd.01.05 | Exchange information | Operator |

Excerpt of the requirement table for the indoor multi-usages drone.

Razafimahazo E., P. de Saqui-Sannes, R.A. Vingerhoeds, J. Soula, R. Mège, C. Baron, "Towards a Customizable Architecture for Indoor Multi-Usages Drones", accepted for ICAS 2022.



## Step-by-step getting to a logical architecture




Initial logical architecture of the indoor multi-usages drone system.

Razafimahazo E., P. de Saqui-Sannes, R.A. Vingerhoeds, J. Soula, R. Mège, C. Baron, "Towards a Customizable Architecture for Indoor Multi-Usages Drones", accepted for ICAS 2022.

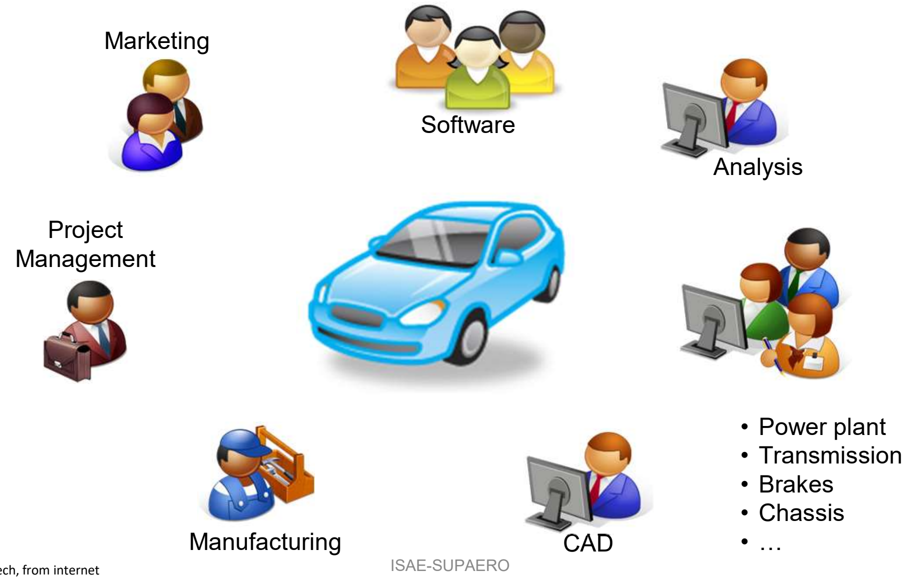
## From Model-Based Systems Engineering

*to Concurrent Engineering…*

Building on the benefits of models…

## Model-Based Systems Engineering

**Moving from Documents to Models (1/3)**




Source: Chris Paredis, Georgia Tech, from internet

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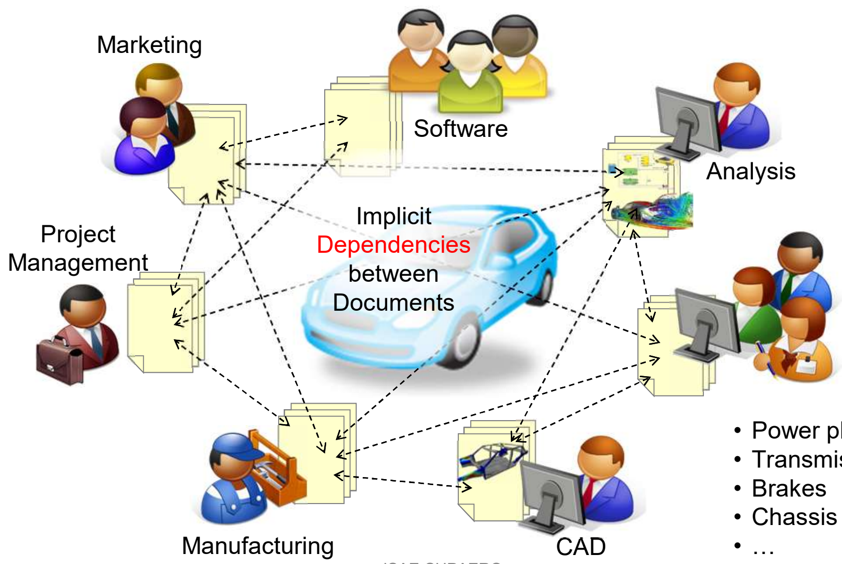
# Model-Based Systems Engineering
## Moving from Documents to Models (2/3)

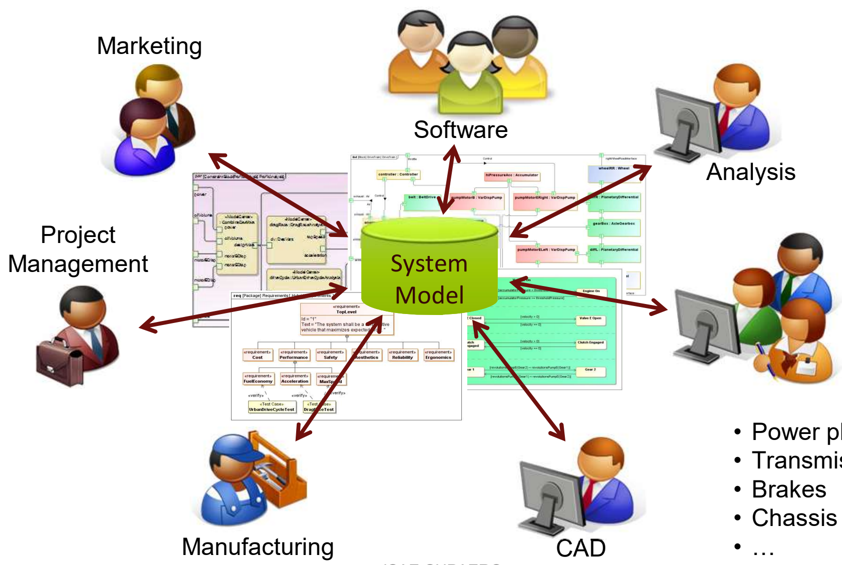



- Power plant
- Transmission
- Brakes
- Chassis
- …

Source: Chris Paredis, Georgia Tech, from internet



# Model-Based Systems Engineering
## Moving from Documents to Models (3/3)



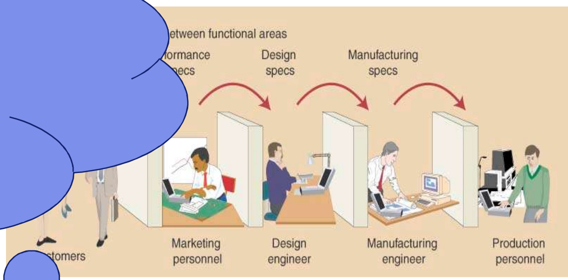

- Power plant
- Transmission
- Brakes
- Chassis
- …

Source: Chris Paredis, Georgia Tech, from internet

# But then, also, why in sequential mode?

**Eight pri... of C... fol...**

'Concurrent engineering is a systematic approach to integrated product development that emphasises the response to customer expectations. It embodies team values of cooperation, trust and sharing in such a manner that decision-making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle.'




- **Team ...**
- **Consistency of goals between departments**

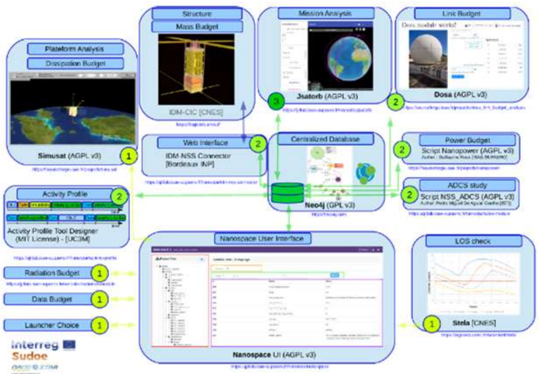
**And:**

- **Downstream requirement consideration**
- **Cross functional teamwork**
- **Customer requirement consideration**
- **Lead time as competitive advantage**

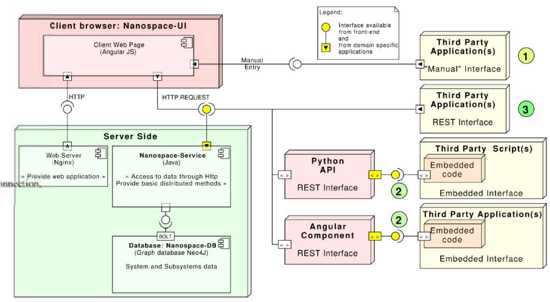
Pictures taken from internet



# An example in CubeSat Development



A Nanospace Constellation for the Nanostar project: the Nanostar Software Suite (NSS). Green circles explicitly illustrate the degree of interconnection, from low connectivity (1) to a fully integrated process (3).




Simplified Nanospace Architecture. The green circles represent the three ways available to connect third-party applications. (1) Manually interacting with Nanospace-UI. (2) Through a provided generic interface (Python API, or Angular Component). (3) Through the Nanospace REST interface.

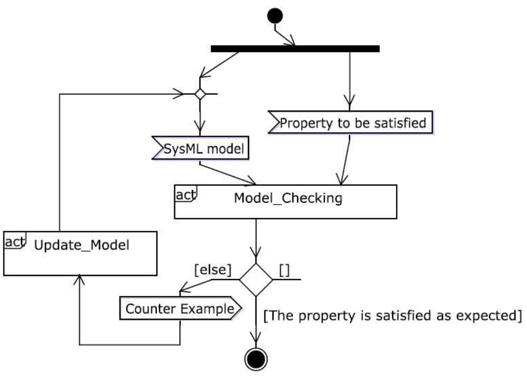
Thibault Gateau, Lucien Senaneuch, Sophia Salas Cordero, Rob Vingerhoeds, "Open Source Framework for the Concurrent Design of CubeSats", 2021 IEEE International Symposium on Systems Engineering (ISSE), 13-15 September 2021, DOI: 10.1109/ISSE51541.2021.9582549.

## Analysing the models

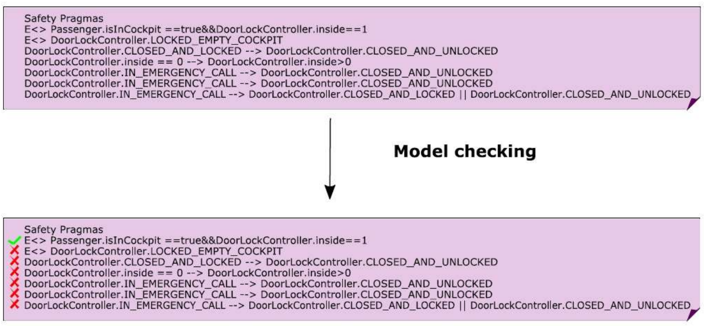
*and get answers as to the complexity…*

Using MBSE should be more than just drawing diagrams…

## Analysing Safety and Security Properties




Model checking SysML models.




Properties expressed and checked in the SysML model.

P. de Saqui-Sannes, L. Apvrille, R. Vingerhoeds, "Checking SysML Models against Safety and Security Properties", Journal of Aerospace Information Systems, AIAA, DOI: 10.2514/1.I010950, On-Line 5 November 2021.

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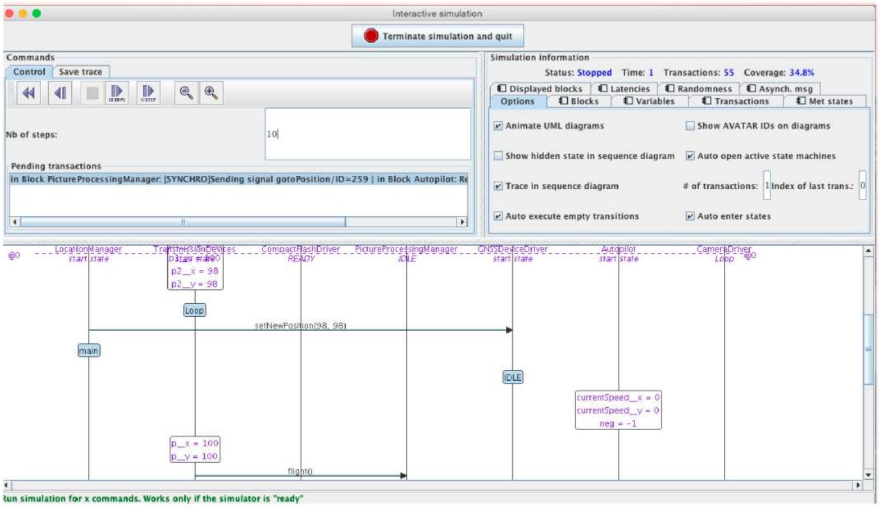
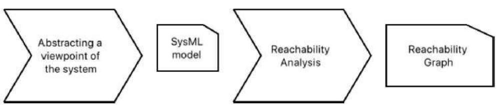
# Simulation of the systems behaviour



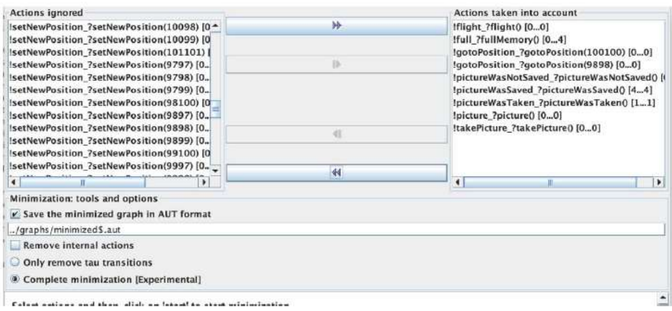

L. Apvrille, P. de Saqui-Sannes, R. Vingerhoeds, "An Educational Case Study of Using SysML and TTool for Unmanned Aerial Vehicles Design", IEEE Journal on Miniaturization for Air and Space Systems, Vol. 1, No. 2, pp. 117-129, DOI: 10.1109/JMASS.2020.3013325, 2020.

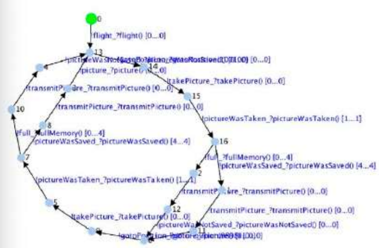


# Verification by abstraction, the reachability graph




Reachability analysis.



Verification by abstraction.

L. Apvrille, P. de Saqui-Sannes, R. Vingerhoeds, "An Educational Case Study of Using SysML and TTool for Unmanned Aerial Vehicles Design", IEEE Journal on Miniaturization for Air and Space Systems, Vol. 1, No. 2, pp. 117-129, DOI: 10.1109/JMASS.2020.3013325, 2020.

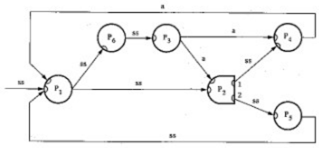
# Analysis of real-time behaviour before realisation of the system(s)

- Guaranteeing a proper functioning of (distributed) systems
  - « logical » coherence
  - temporal coherence (often "forgotten")

The inherent asynchronous communication and the choice of the micro-processors leads to the need for specific formal analysis methods

- An approach to assess during development on the real-time behaviour of systems and their interactions with other systems is necessary so to ensure proper functioning during operation.

- Different approaches exist for such analysis, with specific characteristics ➔ goal to link them to a model-based systems engineering approach



Frame transfer in a communications system

Motus, L, Vingerhoeds, R.A., Meriste, M., «Challenges for Real-Time Systems Engineering, Part 1: State-of-the-Art», Proceedings of the Estonian Academy of Sciences and Engineering, Vol. 11, Nr. 1, pp. 3-17, 2005.
Motus, L, Vingerhoeds, R.A., Meriste, M., «Challenges for Real-Time Systems Engineering, Part 2: Towards Time-Aware Technology», Proceedings of the Estonian Academy of Sciences and Engineering, Vol. 11, Nr. 1, pp. 18-30, 2005.
Motus L., M.G. Rodd, "Timing Analysis of Real-Time Software", Pergamon Press, 1995.



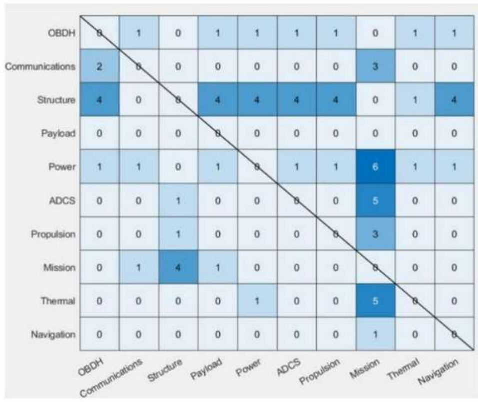
# Design Structure Matrix (DSM)

- A network modelling tool used to represent the elements comprising a system and their interactions, thereby highlighting the system's architecture or designed structure.

- DSMs are particularly well suited for applications in complex systems development and in the area of engineering management.

- Due to their structure, DSM's allow for analysing using matrix operations.

- Their creation, however can be very cumbersome and error prone.

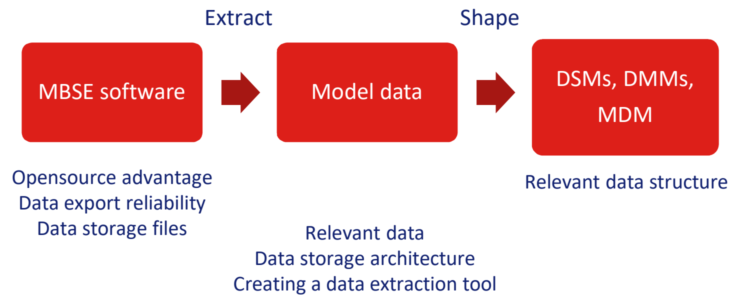


| | OBDH | Communications | Structure | Payload | Power | ADCS | Propulsion | Mission | Thermal | Navigation |
|---|---|---|---|---|---|---|---|---|---|---|
| OBDH | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| Communications | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 |
| Structure | 4 | 0 | 0 | 4 | 4 | 4 | 4 | 0 | 1 | 4 |
| Payload | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Power | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 6 | 1 | 1 |
| ADCS | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 5 | 0 | 0 |
| Propulsion | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 3 | 0 | 0 |
| Mission | 0 | 1 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Thermal | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 5 | 0 | 0 |
| Navigation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |

S.K. Salas Cordero, C. Fortin, R. Vingerhoeds, "Concurrent Conceptual Design Sequencing for MBSE of Complex Systems through Design Structure Matrices", Proceedings of the Design Society: DESIGN Conference, Vol. 1, pp. 2375-2384, Cambridge University Press, doi:10.1017/dsd.2020.96, October, 26-29 2020.

# Automatic generation of DSM's

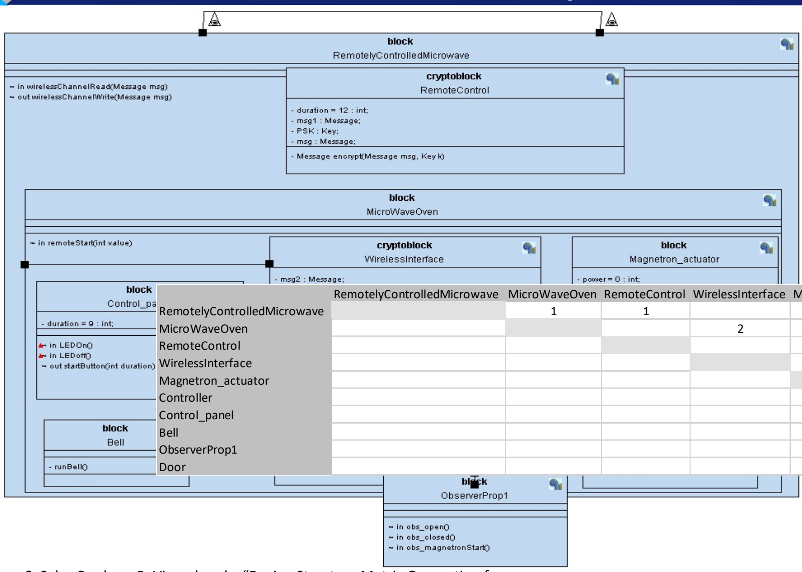
- Building upon models developed in a MBSE environment, the DSM's can be generated automatically without loss of information.




W. Pons, S. Salas Cordero, R. Vingerhoeds, "Design Structure Matrix Generation from open-source MBSE tools", 2021 IEEE International Symposium on Systems Engineering (ISSE), 13-15 September 2021, DOI: 10.1109/ISSE51541.2021.9582525



# Example DSM generation (Numeric Directed Components DSM)

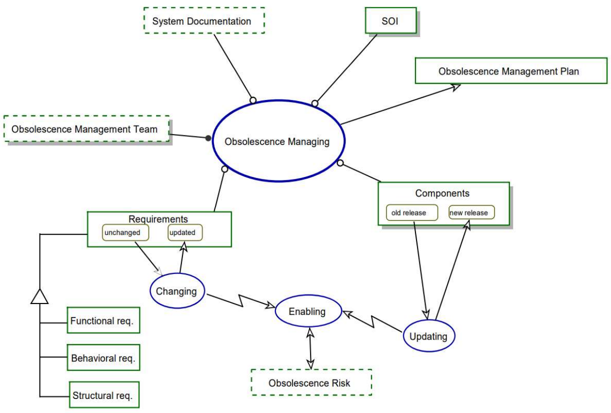



| | RemotelyControlledMicrowave | MicroWaveOven | RemoteControl | WirelessInterface | Magnetron_actuator | Controller | Control_panel | Bell | ObserverProp1 | Door |
|---|---|---|---|---|---|---|---|---|---|---|
| RemotelyControlledMicrowave | | 1 | 1 | | | | | | | |
| MicroWaveOven | | | | 2 | 1 | 1 | 1 | 1 | | 1 |
| RemoteControl | | | | | | | | | | |
| WirelessInterface | | | | | | | | | | |
| Magnetron_actuator | | | | | | 2 | | | | |
| Controller | | | | | | | 1 | | | 2 |
| Control_panel | | | | | | | | | | |
| Bell | | | | | | 1 | | | | |
| ObserverProp1 | | | | | | 3 | | | | |
| Door | | | | | | | | | | |

W. Pons, S. Salas Cordero, R. Vingerhoeds, "Design Structure Matrix Generation from open-source MBSE tools", 2021 IEEE International Symposium on Systems Engineering (ISSE), 13-15 September 2021, DOI: 10.1109/ISSE51541.2021.9582525

## Analysis of obsolescence risks

- The term of obsolescence goes beyond only the availability of a component from its OEM
  - Functional: due to changes in the system requirements or changes in other parts of the system.
  - Technological: when more technologically advanced components have become available and older parts are no longer supported.
- Identification of obsolescence risks early on in the design process allows for proactively addressing these risks
- Building upon models developed in a MBSE environment, methods can be proposed to identify these risks
- Such approaches allow for knowing a priori the risk that a certain part represents in an architecture could impact on the obsolescence management plan.




Sophia Salas Cordero, Marc Zolghadri, Rob Vingerhoeds, and Claude Baron, "Identification and Assessment of Obsolescence in the Early Stages of System Design", Journal of Integrated Design & Process Science, DOI: 10.3233/JID-210018, in Pre-Press (2021/2).

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## In conclusion

*and trying to summarise…*

… what I was trying to explain

# Conclusions

- Novel (networked and intelligent) technologies are step-by-step taking a bigger place in our lives, but increase design complexity of the concerned system(s)
- A structured design approach starting with analysis of needs, desires and values leading into requirements is proposed, linked to a recurrent use of three in parallel running design processes on requirements design, the artefact design and the design coordination.
- The use of MBSE is recommended from the earliest starts, but not only to draw, but to do analyses as well on the logical coherency and completeness, the time-wise behavior, links to complementary tools, etc
- The adoption of concurrent engineering offers interesting possibilities



# Research orientations

More fundamental work is necessary on

- better consideration of requirements and alert on breaches of constraints,
- multidisciplinary approaches (and seamless connection / data continuity),
- prediction of systems behavior in terms of functionality, as a whole and of the components in their environment, ...
- allow to concentrate on the different components of the systems,
- support
  - the individual technical skills for each discipline,
  - optimization and reuse,
  - multi-technology concurrent engineering,
  - intuitive use,
- better integrate project management tools,
- support and integrate new approaches, such as agile development,
- ...

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