

# **Toward the standardization of digital verification technology**

**- Development of guidelines for creating 1D CAE  
models of mechano-electrical products -**

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# Agenda

1. Background
2. MBD and 1D CAE for mechano-electrical products
3. Guidelines for making 1D CAE models of mechano-electrical products
4. Findings in our empirical study
5. Conclusions

# Background

- Small, precise, and high-performance mechano-electrical products are products in which Japan has traditionally excelled in.
  - Multifunctional copiers, printers, digital cameras and other photo equipment, automatic teller machines...
- In the development of these products, higher functionality and lower prices are required, and technologies for supporting efficient product design are strongly expected.

Multifunctional copier



Inkjet printer



Automatic teller machine



Photo equipment

# High-tech industry problems in Japan - *Each Design Process*

## Common problems found in 90% of answers in census

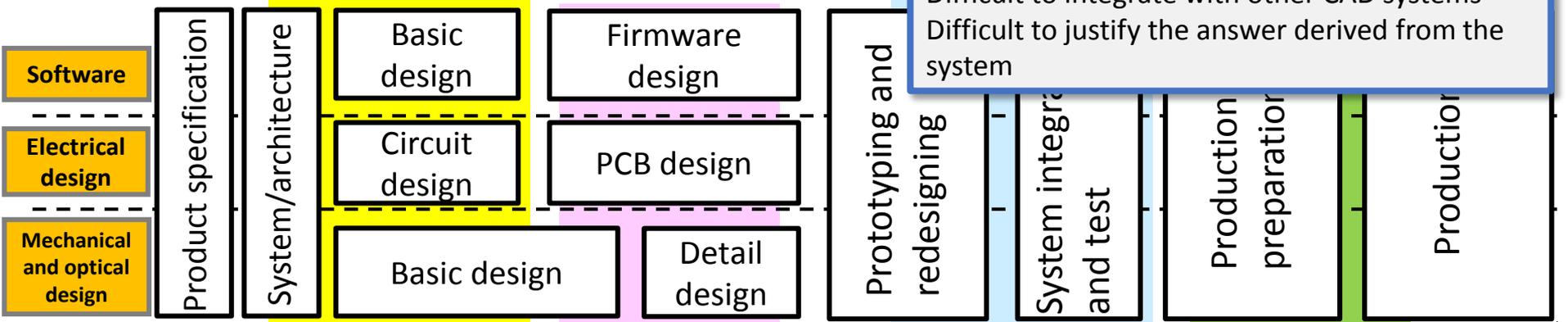
- Cost of finding an effective solution based on the results of multiple analyses
- No common framework for handling multiple phenomena in different physical domains simultaneously

## Independent development of original solutions in each company

- Development of original system (+ commercial system), original models, original formulation, use of empirical formula, and know-hows

### Problems of using original systems

- Difficult to maintain the system
- Difficult to integrate with other CAD systems
- Difficult to justify the answer derived from the system



time

**Function and performance considerations**

**Packaging and control design (part placement)**

**System evaluation (heat, EMI)**

**Producibility evaluation (assembly, mounting)**

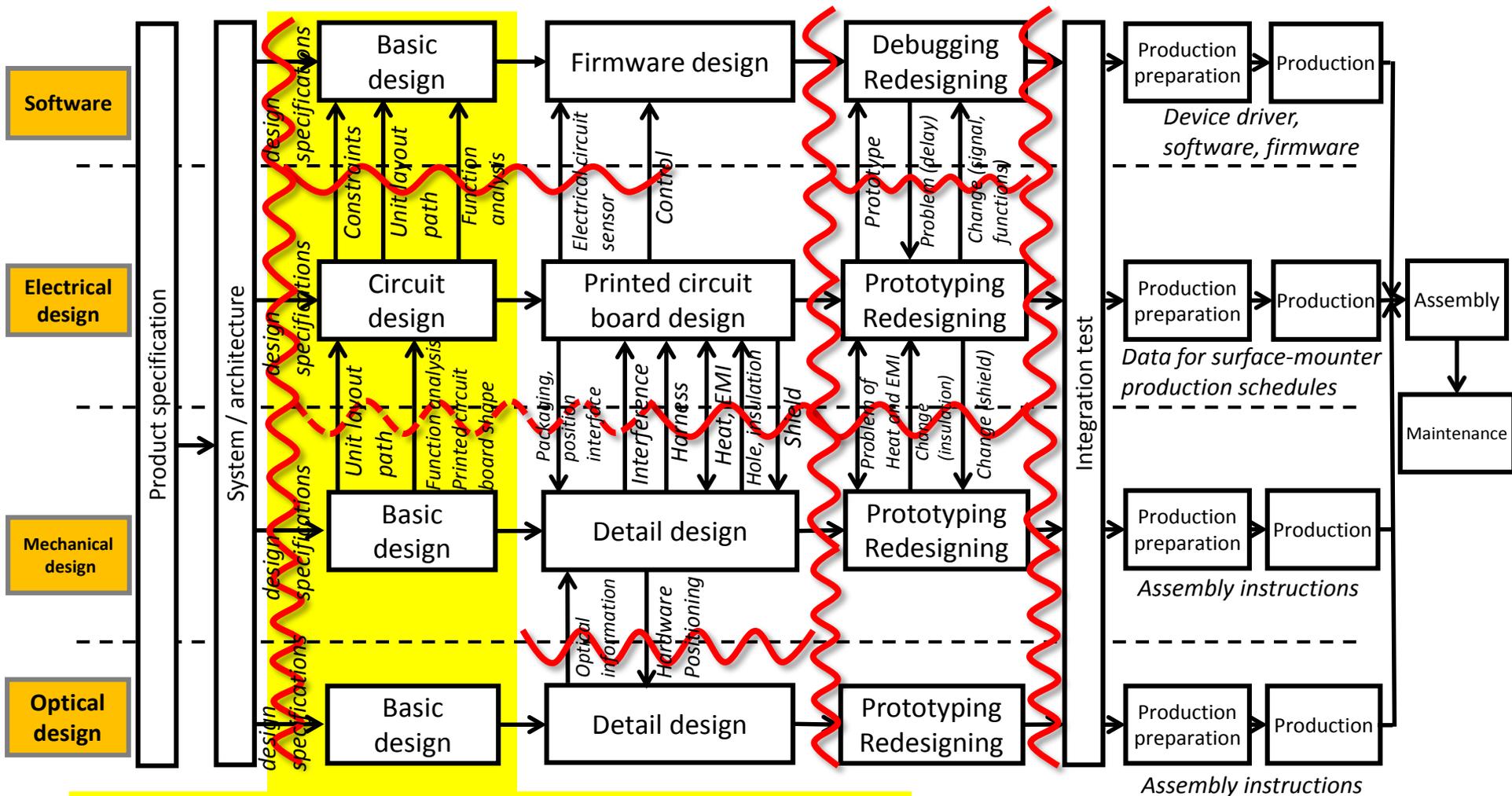
## Common problems found in 90% of answers in census

- 3D modeling of soft objects, e.g., harness and cables
- Management of electrical and mechanical parts in 3D library
- Difficulty in evaluating tolerances specified on 3D parts
- Difficulty in integrated use of multiple CAD and CAE tools
- Difficulty in generating patterns for tests

## Common problems found in 90% of answers in census

- Frequent redesign.
- Difference of I/O interface of CAM systems and cost of preparing data in their original format

# High-tech industry problems in Japan - *Inter Design Processes*



- Digital data exchange is not smoothly done between CAD/CAE systems in early design stage
- Manual data translation is still necessary in many fields

Development of original interfaces, original-data sharing methods, and manual-data exchange methods in each company

# High-tech industry problems in Japan - *Joint Development*



**Automatic ticketing gate (OEM)**



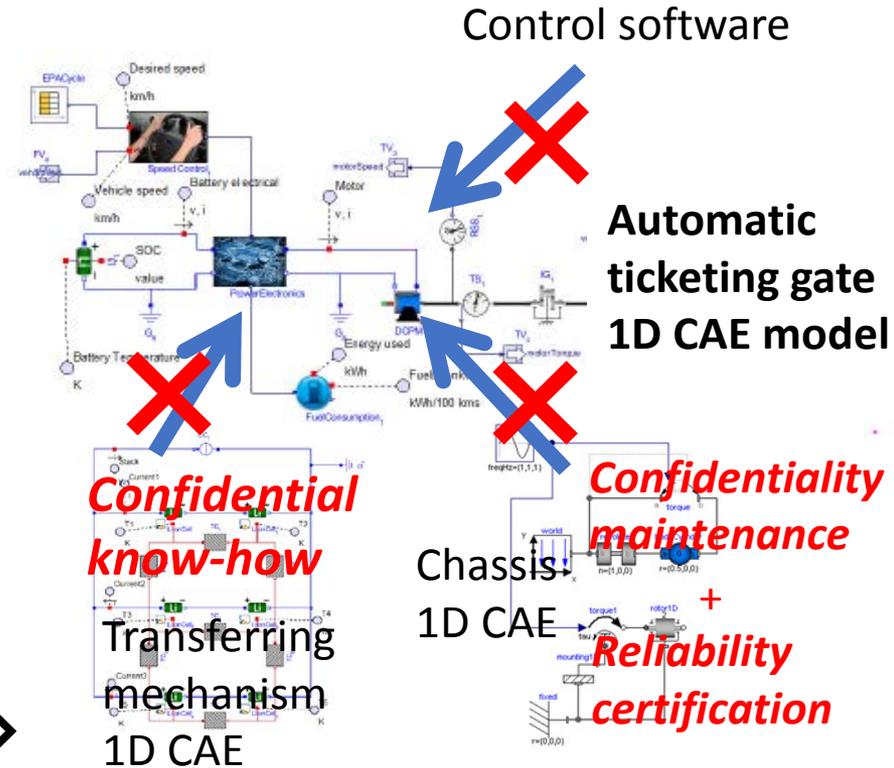
**Ticket transferring mechanism (A company)**



**Chassis (B company)**



**Control software (C company)**



- **Development by a single company:** Purchase parts from suppliers. CAD models of parts are obtained for determining the fixing and assembly method.

- **Joint collaborative development by multiple companies:** Engineering information (CAE data) of all components is necessary for total analysis of the product. Use of Functional Mock-up Interface (FMI) standard is one possible solution, but confidentiality maintenance and reliability certification of FMI are still uncertain.

# Seven requirements on digital verification technology

- It is important to actively use computer simulations in the early conceptual and functional design processes to evaluate the feasibility of the function and narrow down the appropriate design solutions at an early stage.
- Such simulation technology must satisfy;
  1. Simulation technology which is applicable in very early design stage when the product shape is uncertain.
  2. Physical properties in multiple domains (electrical, mechanical, optical, and software) can be handled in a uniform framework.
  3. Unformatted declarative knowledge such as “know-how” can be handled in the same framework.
  4. Design process decisions can be recorded with their justifications (helpful for solving problems occurring in usage).
  5. System can be used as a standard software tool for building models in most mechano-electrical product companies in Japan.
  6. Original design knowledge specific to each company can be described and integrated in the system and confidentiality can be maintained.
  7. System can be integrated with major existing 3D CAD and CAE systems.

# Use of 1D CAE

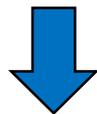
- In the design of automobiles/aircrafts, it is popular to use model-based development (MBD).
- In MBD, various conditions related to the requirements and functions are defined by mathematical models. By evaluating the models, product functions can be verified at the early design stage.
- Since simple analyses often begin before 3D information is determined, the application of MBD at the early conceptual/functional design stage is known as 1D CAE.



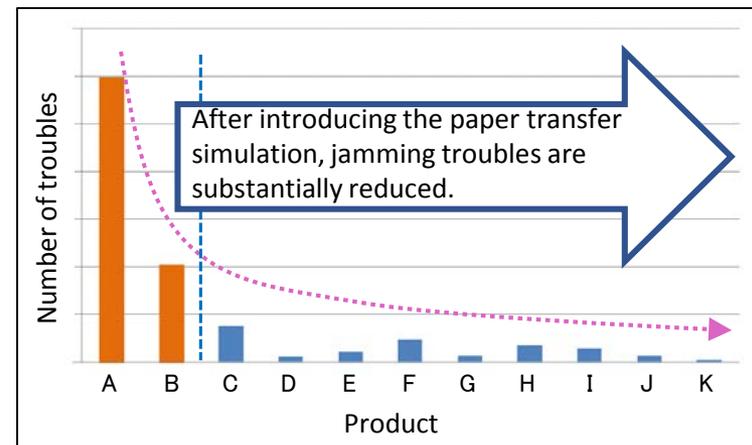
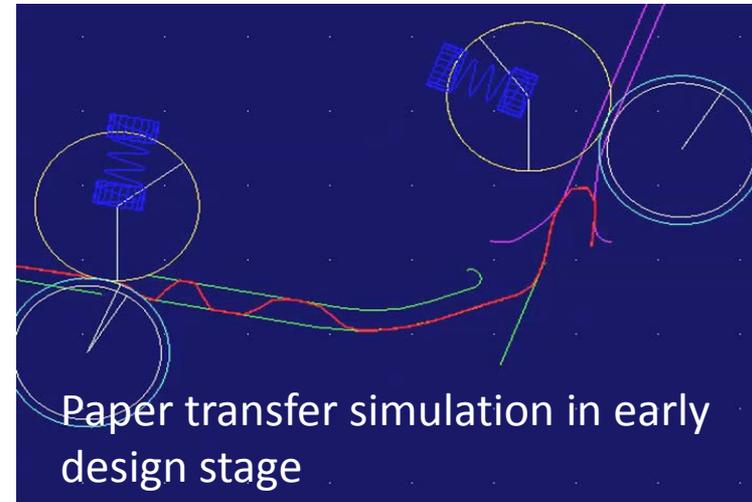
# MBD for supporting mechano-electrical product design

- In the design of the paper transfer mechanism of a copier, analysis of the paper behavior in the paper transferring process is necessary.

- In prior days, paper behavior was checked by using a trial product. When a paper jammed, position and posture of the parts are slightly changed while guessing paper behaviors.



- Today, designers themselves carry out paper transfer simulation to analyze the paper behavior at the initial stage of design.



# Why 1D CAE is not prevalent in mechano-electrical product design?

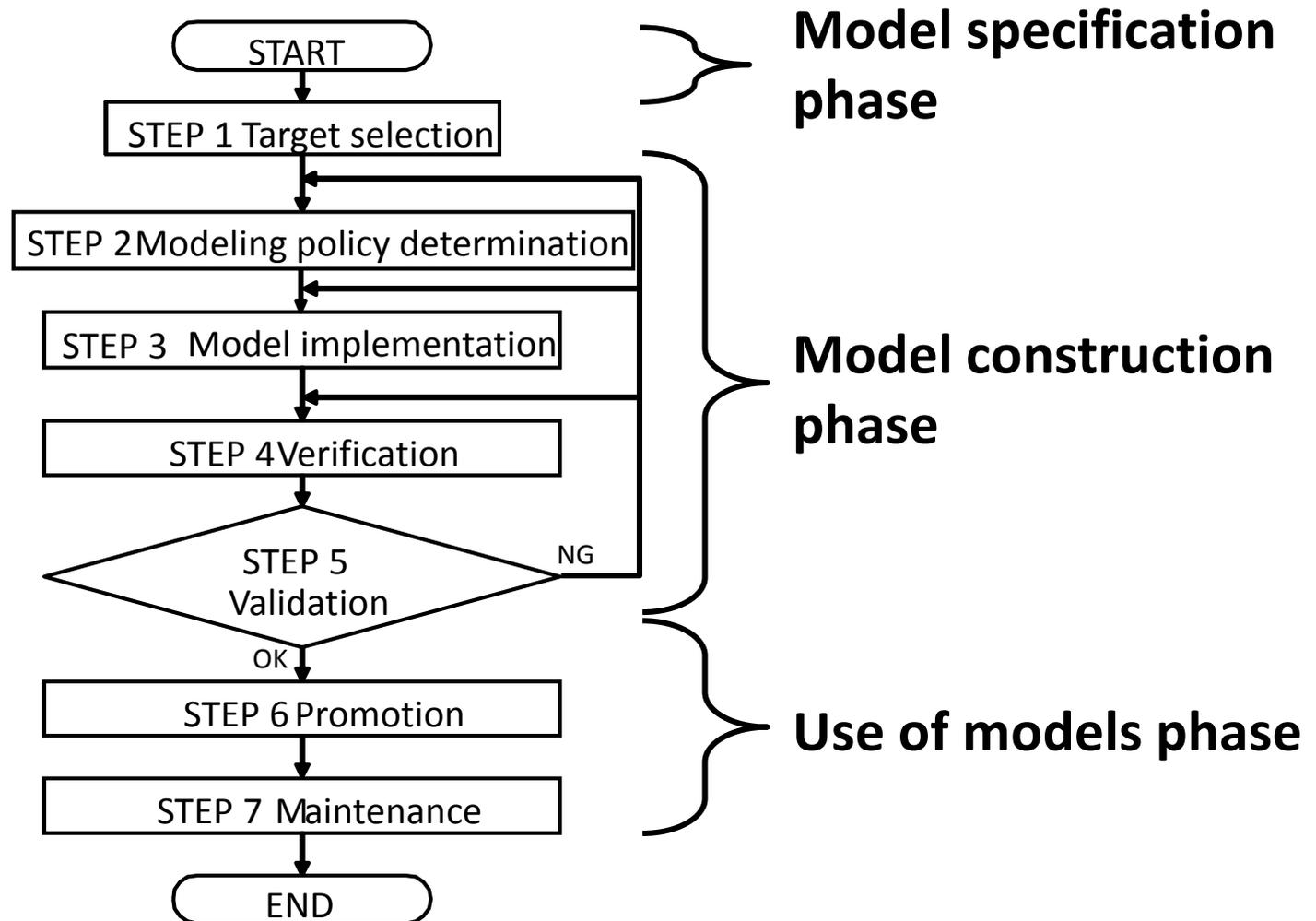
- 1D CAE is effective for supporting the conceptual/functional design of mechano-electrical products, however it is not a popular method.
- Some reasons:
  1. The development cycle of mechano-electrical products is brief compared to automobiles/aircrafts. Necessary cost for preparing the mathematical model for 1D CAE is relatively large.
  2. In the case of mechano-electrical products, the basic structure of the product changes rapidly. Therefore, reuse of prior models for new designs is difficult.
  3. The scale of business of mechano-electrical product manufacturers is small compared to automobile/aircraft industry. It is difficult to secure adequate engineers specializing in 1D CAE.

# Guidelines for using 1D CAE in designing mechano-electrical products

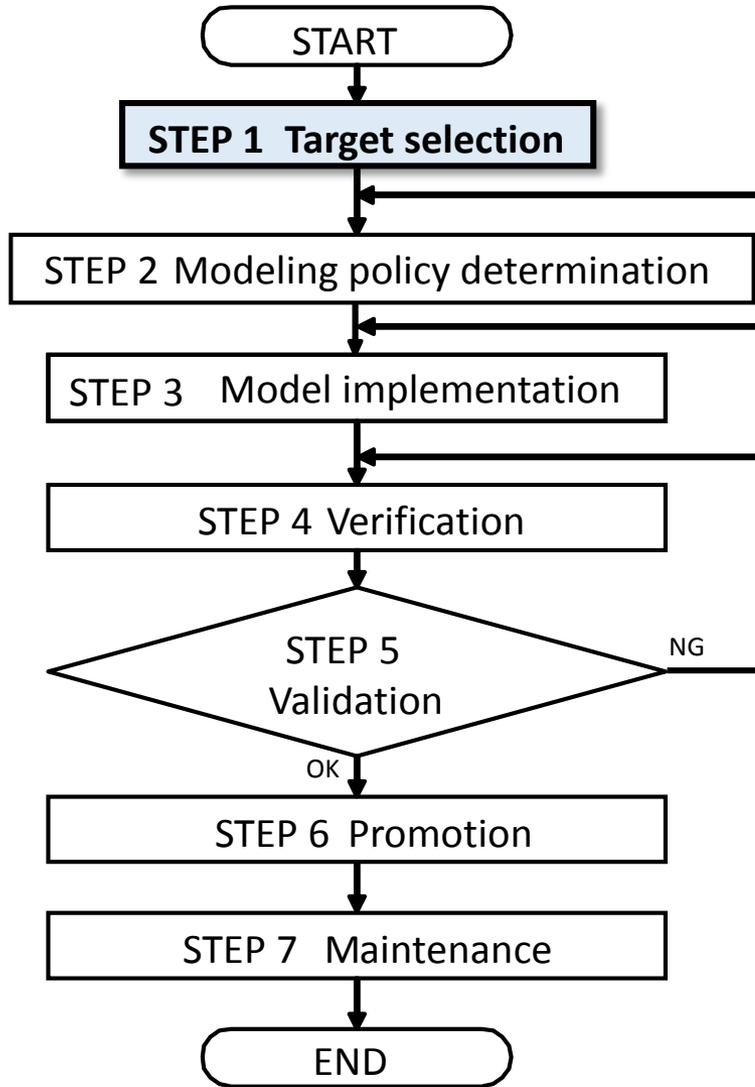
- To promote the use of 1D CAE in the mechano-electrical industry, it is necessary to eliminate the obstacles associated with the use of 1D CAE as much as possible.
- In the effort to reduce the modeling cost, we are developing guidelines for creating proper 1D CAE models for mechano-electrical products.
- We explain our guidelines and use the formulated guidelines to develop simple mechano-electrical components.
- We also explain our findings in the use of 1D CAE in the mechano-electrical industry.

# Guideline, overview

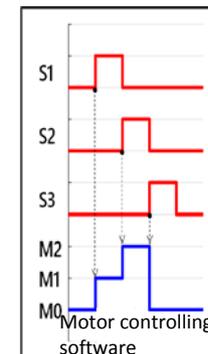
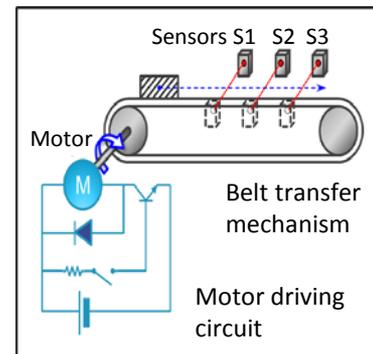
- In our guideline, a typical model development process is formulated in a flowchart style.



# STEP 1 Target selection

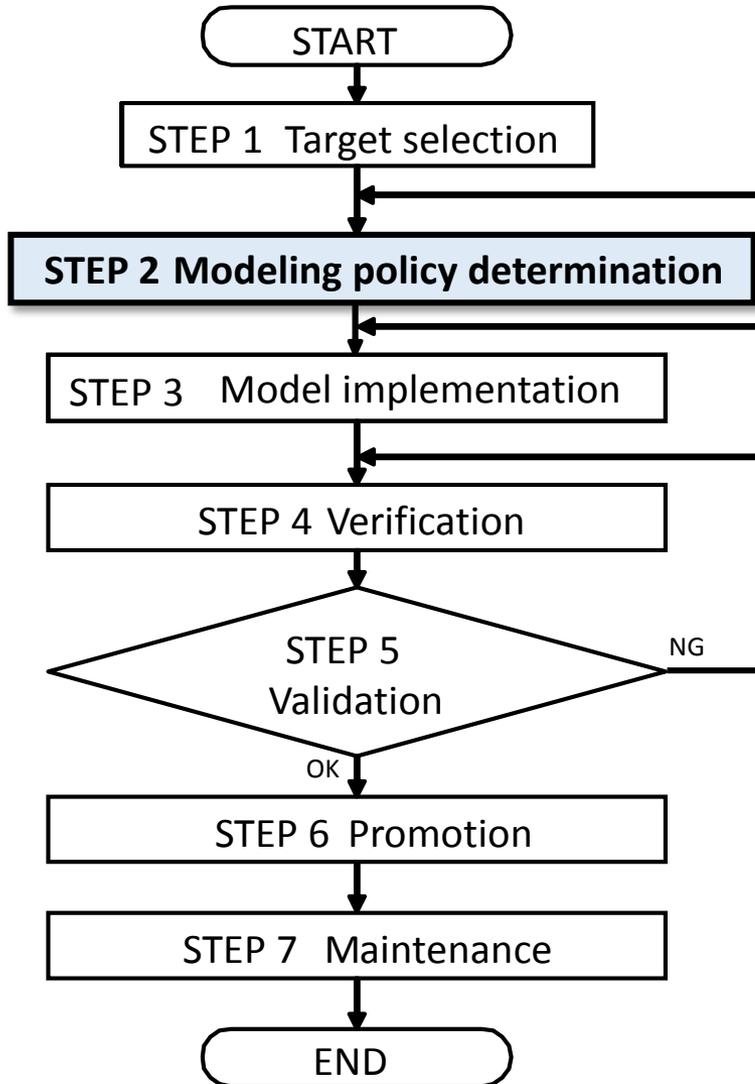


- The design target is determined and the function of the target product is clarified.
  - Carry out *functional development* and convert the function to physical models with proper input and output parameters.
  - Establish communications with the designer in charge of the target product in advance to understand the necessary solution using the 1D CAE model.

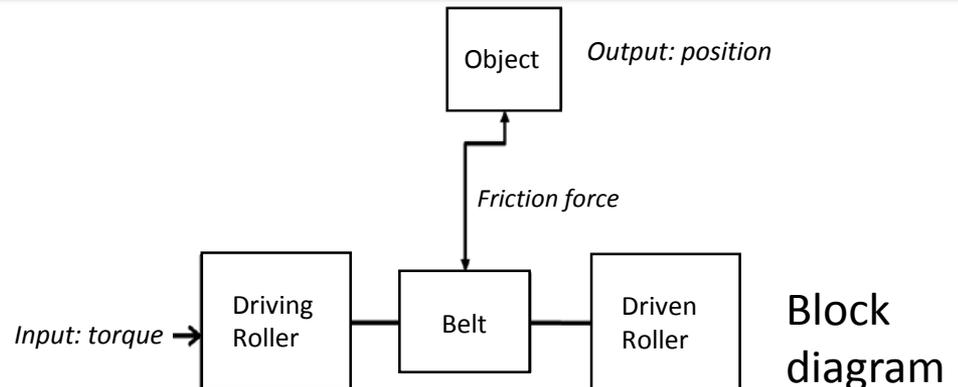


Target mechanism

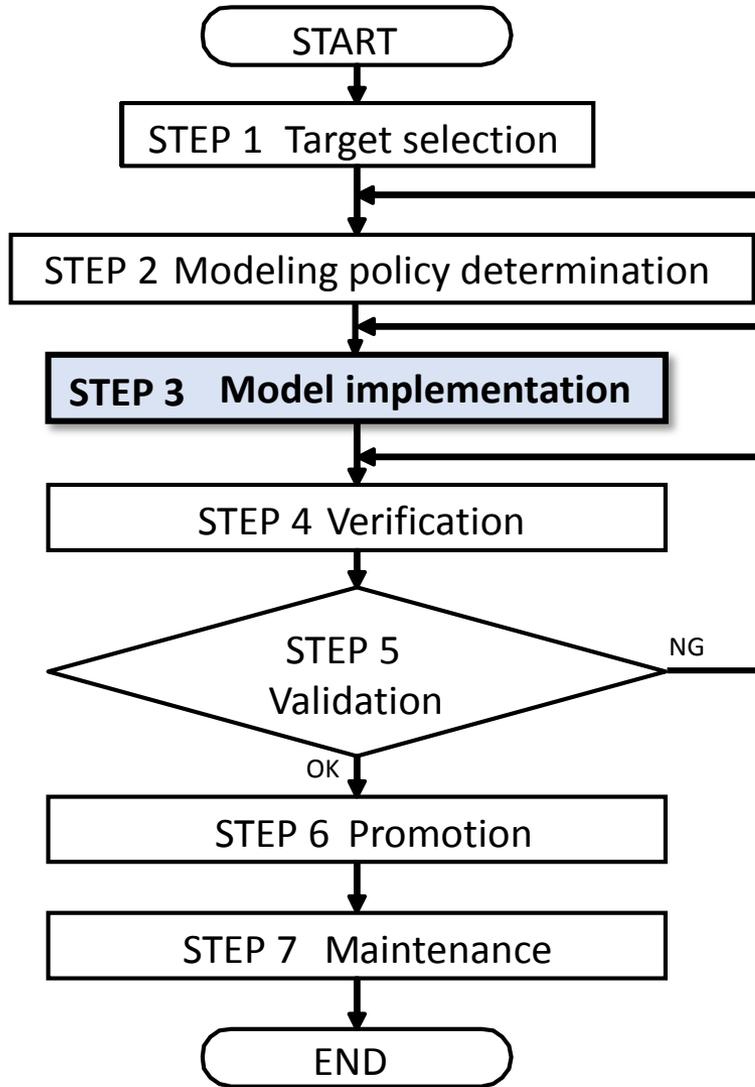
# STEP 2 Modeling policy determination



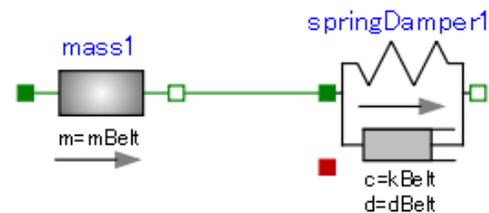
- Determine modeling level of components based on the function development result.
- Determine functional specifications, scope of modeling, design parameters and their value ranges, disturbance, and modeling accuracy.
- Modeling method depends on the functional specifications of the model.
  - (e.g.) Design of gear train
    - Analysis of conveying rotation: modeling of simple gear ratio.
    - Analysis of vibration of gear train: modeling of rigidity of gear teeth.
- Describe functions of the model using block diagram.



# STEP 3 Model implementation

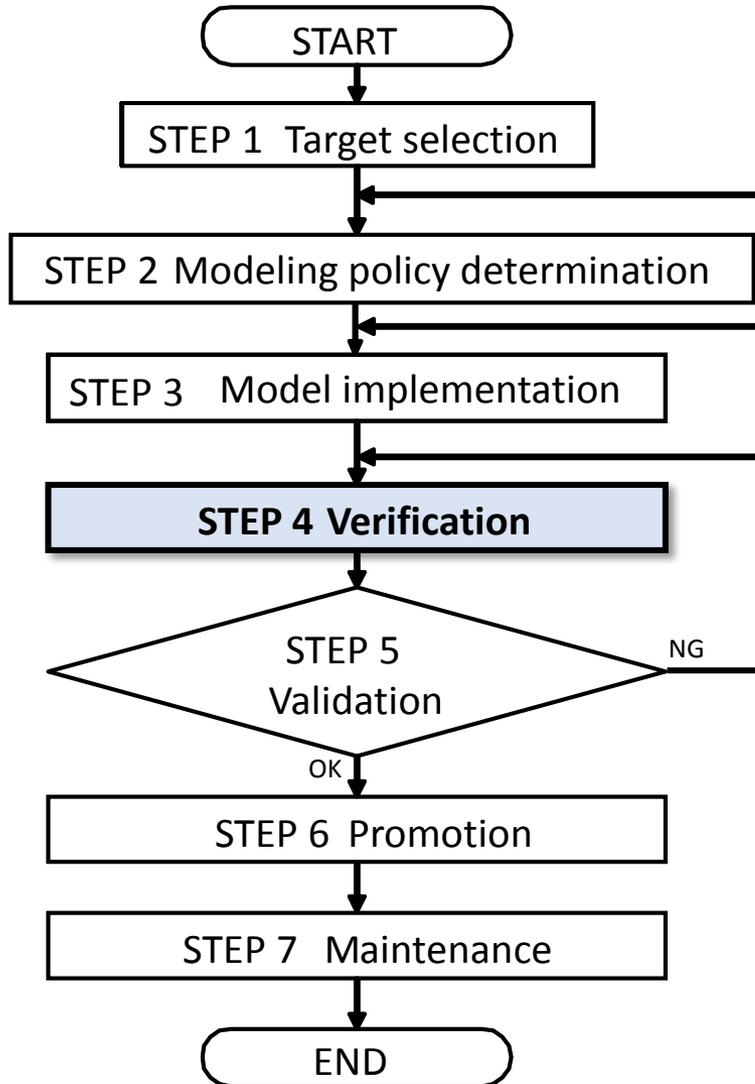


- Implement the model according to the determined modeling policy.
- Modelica-based tools and MATLAB/Simulink are usually used in the implementation.
- Selection of the proper tool is critical.
  - Many commercial 1D CAE systems (Dymola, SimulationX, ...) are based on Modelica, but each has its own characteristics. Selection of a tool appropriate to the target problem is important.
- Modelical-based systems provide a GUI for constructing models. User connects functional parts given by the system in the display to realize a desired 1D CAE model.



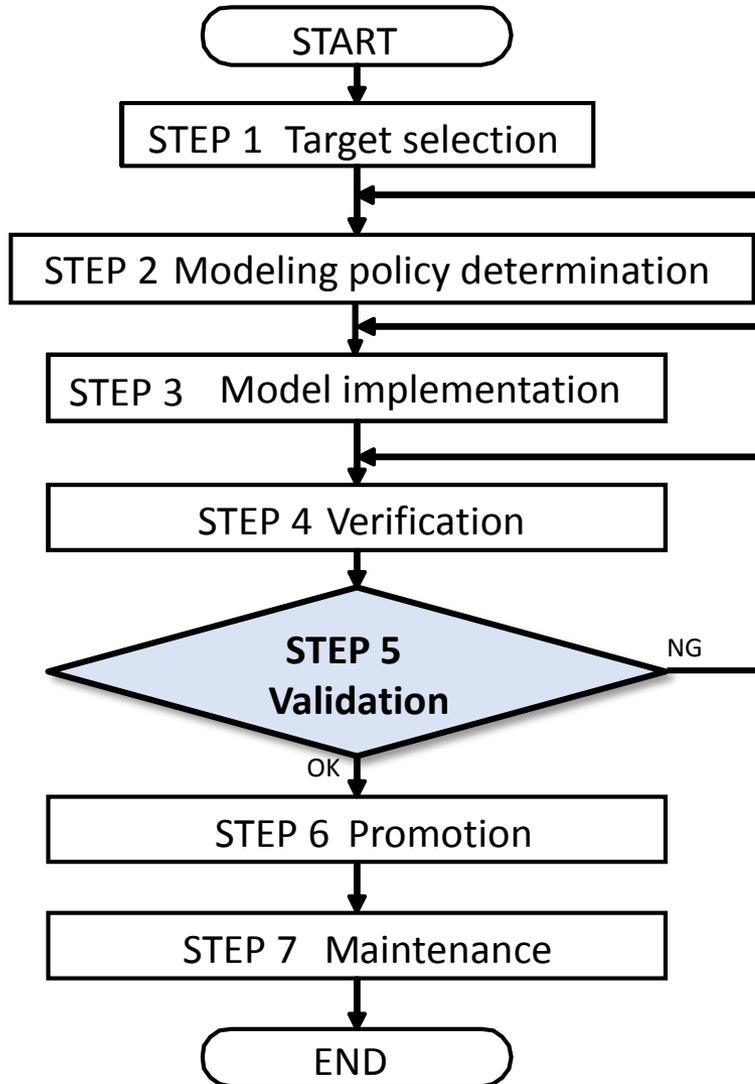
Implementation  
using Modelica

# STEP 4 Verification of the model



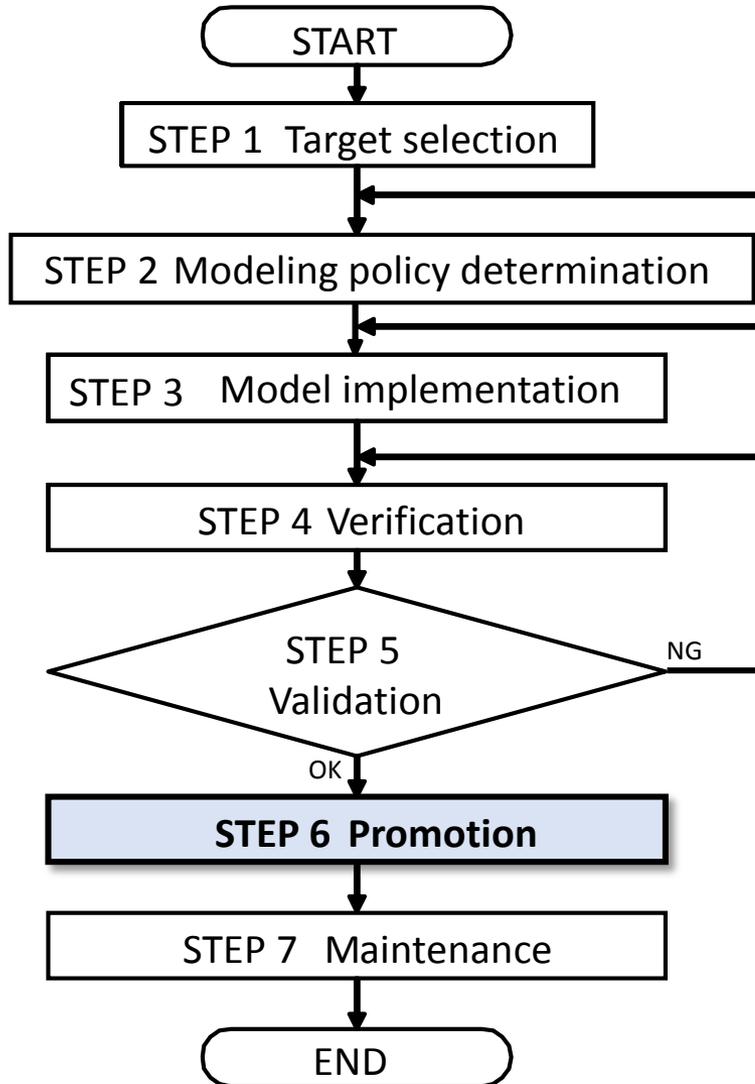
- Verify constructed models. There are two types of verification—operation verification and accuracy verification.
- Operation verification:
  - Does the constructed model move?
  - Does it work properly with multiple design variables within their upper- and lower-limit values?
- Accuracy verification:
  - Confirm that the implemented model reveals stable motion with limited errors against a reference (measured value, theoretical value).
- When the combinations of design variables are enormous, it is necessary to devise an orthogonal table to track the design variable combinations in the verification.

# STEP 5 Validation of the model



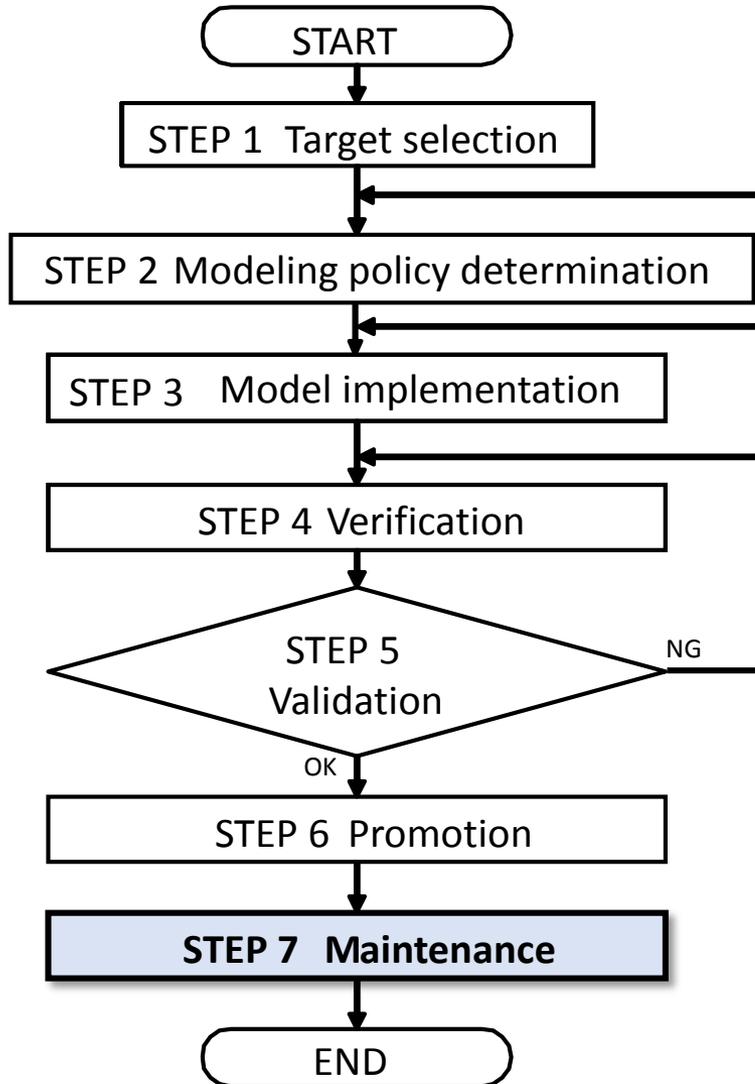
- Construct total model or subsystem model by connecting component models.
- Compare and verify the model at the subsystem level with actual measurement values.
- Check whether the results satisfy the accuracy requirements determined in Step 2. If they do not, repeat from Step 2 to Step 4 to refine the model.
- Compare with actual machines and experiment benches to confirm the accuracy of the model.
- Compare with actual measurement values of prototypes and execute PDCA cycles to improve the model accuracy.

# STEP 6 Promotion to designers



- Constructed models are sent to the design department.
- To encourage the designers to use them, various promotion works are necessary. For example,
  - Distribution of a usage manual,
  - Formulation of a report explaining the theoretical background of the model,
  - Preparation of accuracy reports, and other documents,
  - Preparation of training course for using the system.
- It is important that designers use the model with confidence.

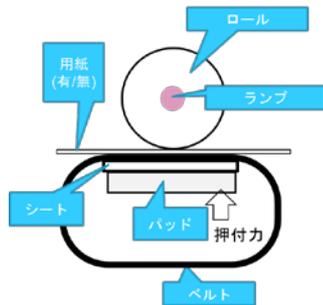
# STEP 7 Maintenance of the model



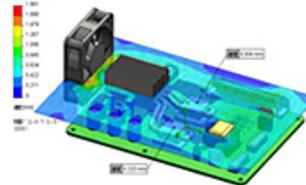
- When the model is deployed in the design, new demands emerge, such as
  - Expansion of functions,
  - Addition of new design variables, and so on.
- To respond to the demands, realization of a model maintenance system with proper human resources is important.
- It is also necessary to establish rules for the control of the models and reuse them.

# Evaluation of the guideline

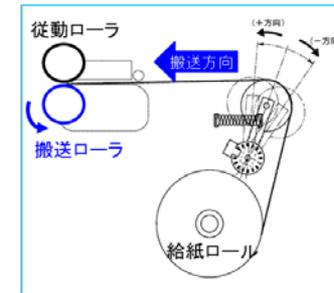
- To evaluate the applicability of the guideline for constructing the 1D CAE model of the mechano-electrical product, we conducted some empirical studies of the modeling.
- We use OpenModelica with Modelica Standard Library (MLS) as a modeling tool for maintaining the model compatibility. We adhere to the modeling process **STEP1** to **STEP3** given in our guideline as much as possible.



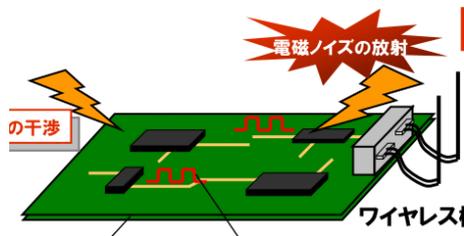
Transfer with belt



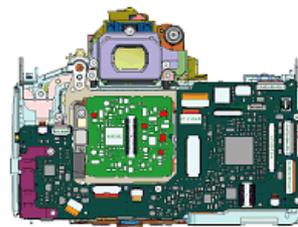
Heat transfer



Belt/Paper transfer



Electromagnetic noise



Electric circuits

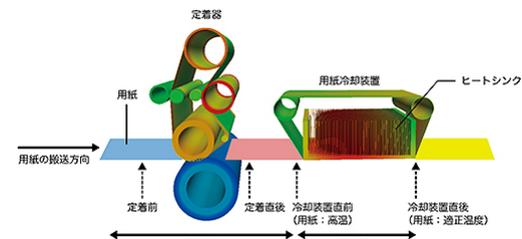
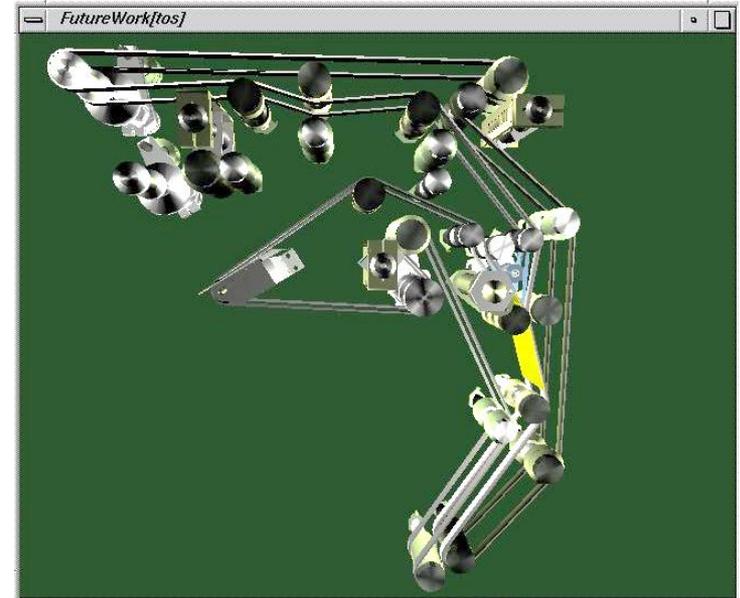


Image fixing

Typical components of the mechano-electrical product

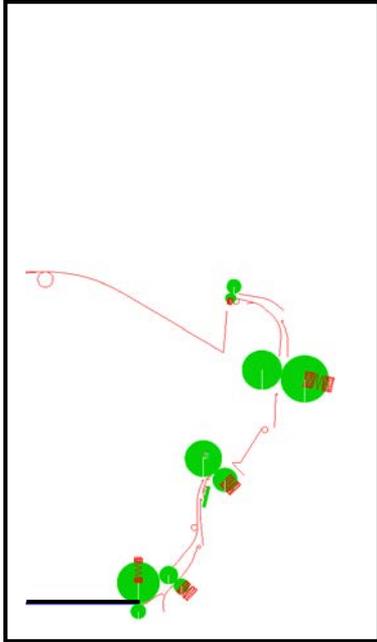
# Belt/Paper transfer mechanism 1

- Complex but important mechanism of the copier machine/printer. Understanding the behavior of the whole mechanism is necessary for developing the control software and the built-in system.
- Passing of object/paper in front of a photo sensor causes a switching of the behavior. Speed and timing analysis of the object/paper is necessary.



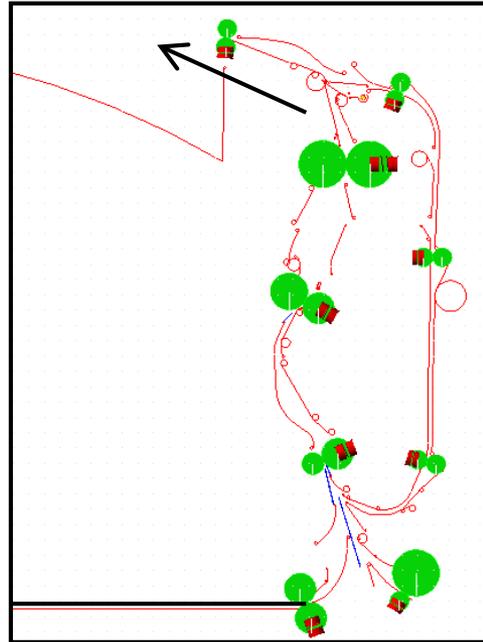
# Belt/Paper transfer mechanism 2

Printer



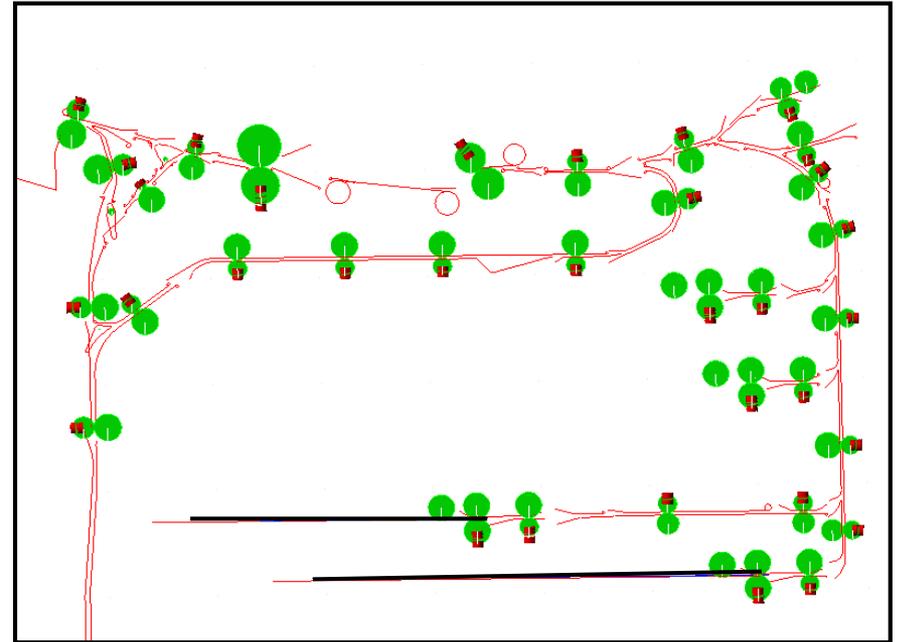
Analysis of path with small radius

Copier machine



Switching mechanism

Professional printing machine

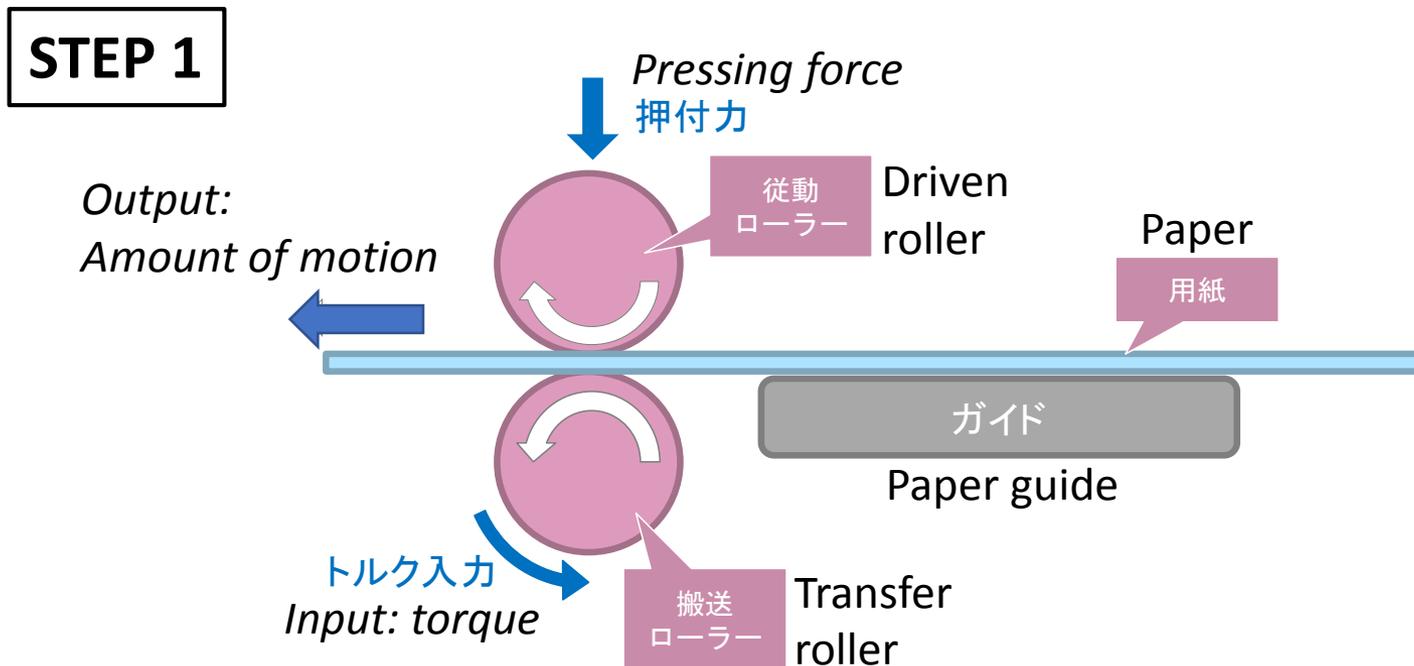


Path analysis of paper in high-speed motion

- Motion analysis of cam and follower, paper transfer analysis, contact analysis at multiple points, and switching mechanism were developed (e.g. RecurDyne system).
- Extension of the current methods for analyzing the entire mechanism is difficult.
- Cooperation with various analysis methods for paper transfer, thermal, frictional, chemical, and electrical behavior is difficult in the current modeling framework.

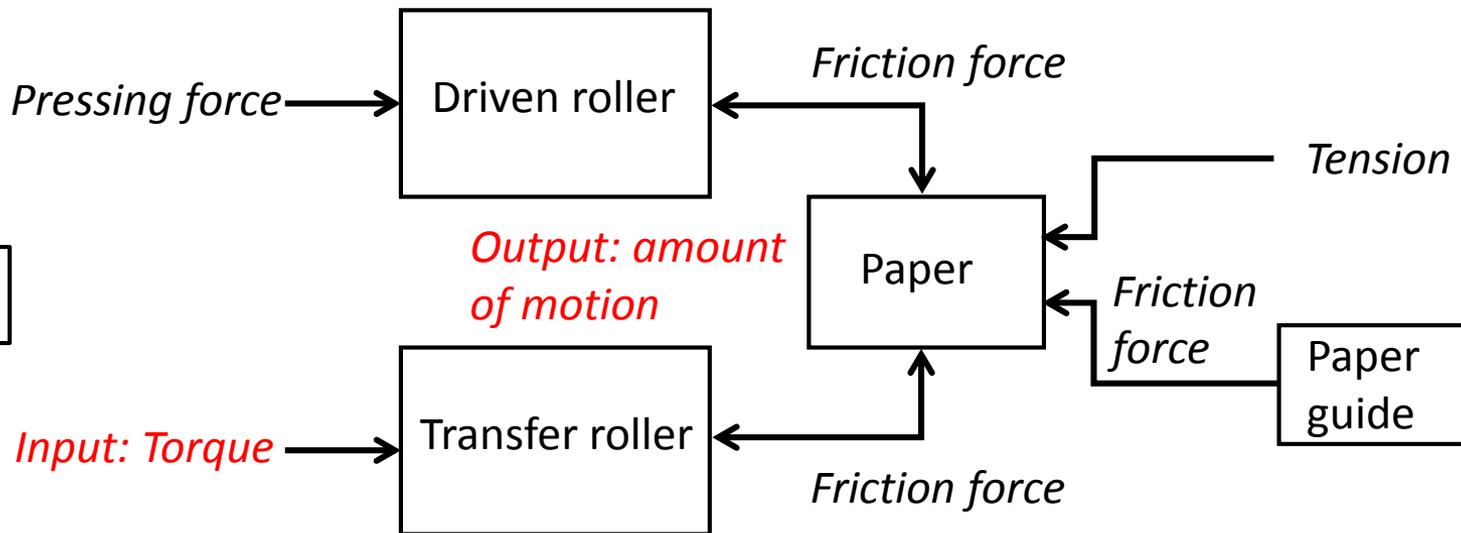
# CASE 1 Simple paper transfer mechanism

- A paper on a guide is transferred according to the rotation of a transfer roller. Pressing force is applied to the paper through a driven roller.



# Block diagram of simple paper transfer mechanism

- We decomposed the paper transfer mechanism to some components and clarified the physical relationships between the components.
- We then defined the functional model of the mechanism using a block diagram.

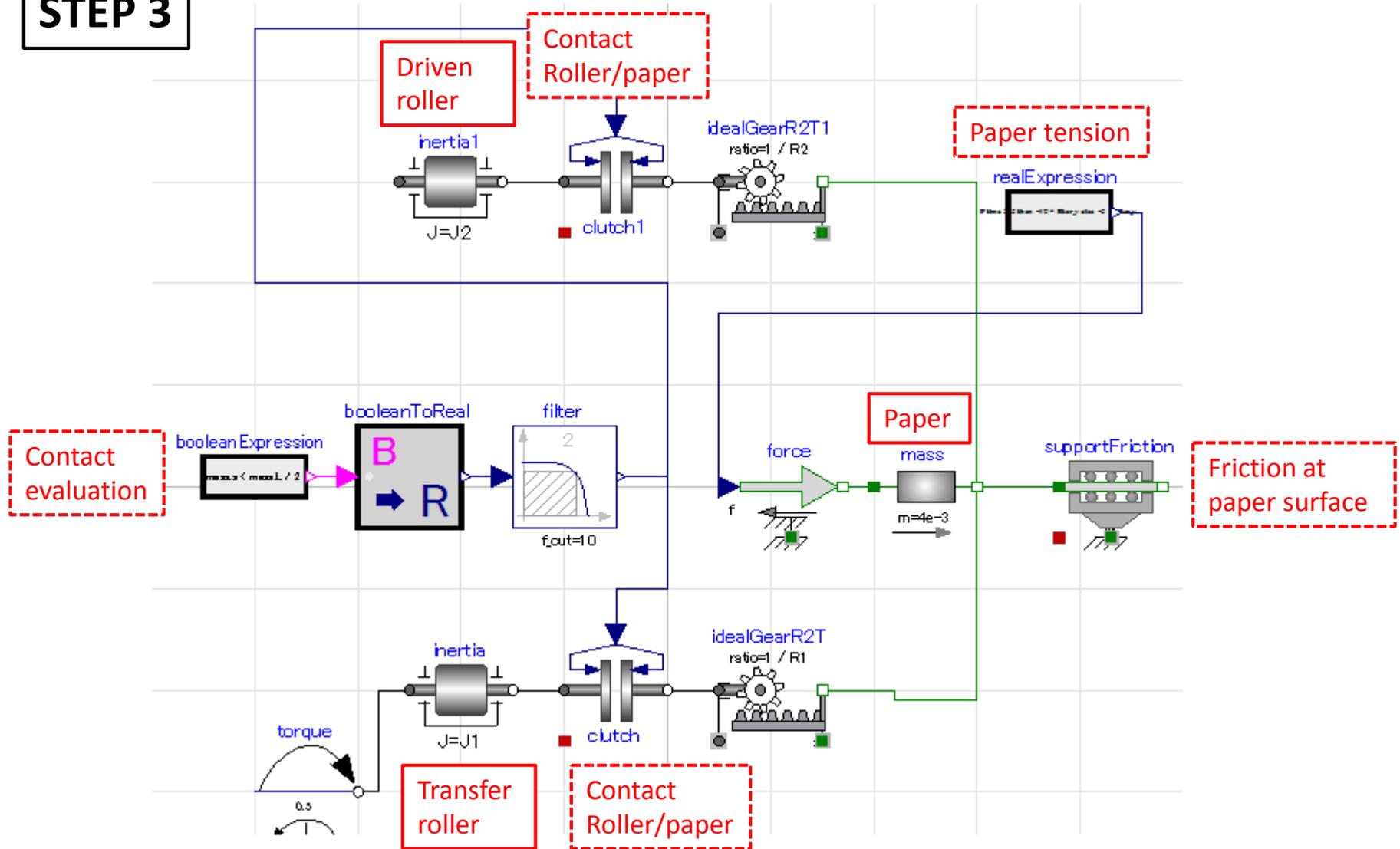


**STEP 2**

*Input: Torque*

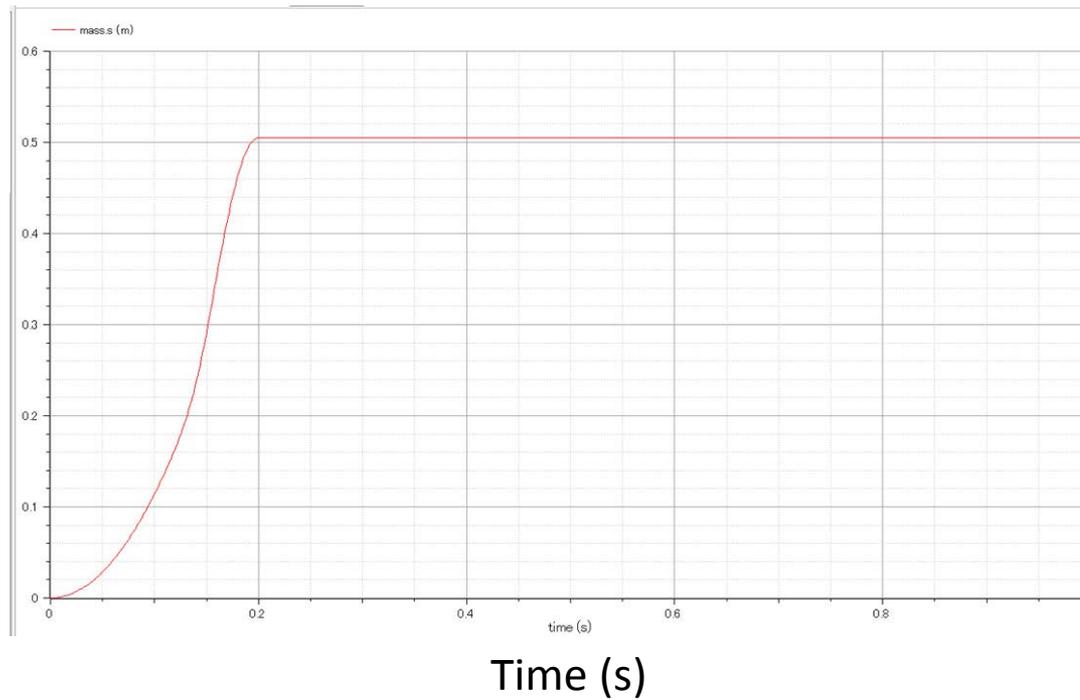
# A paper transfer model in Modelica

STEP 3



# Simulation result

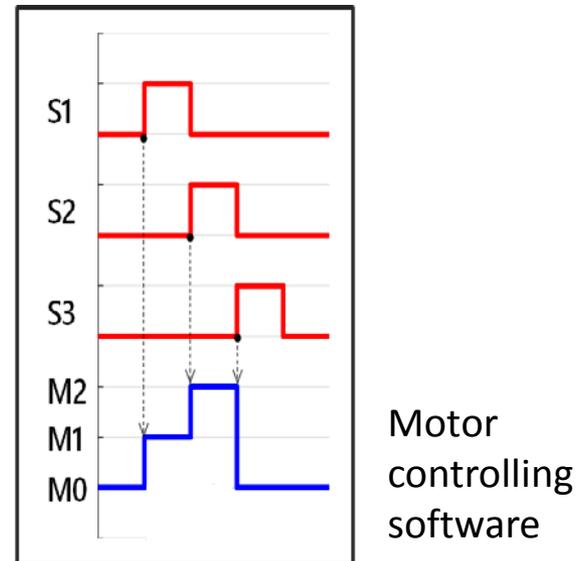
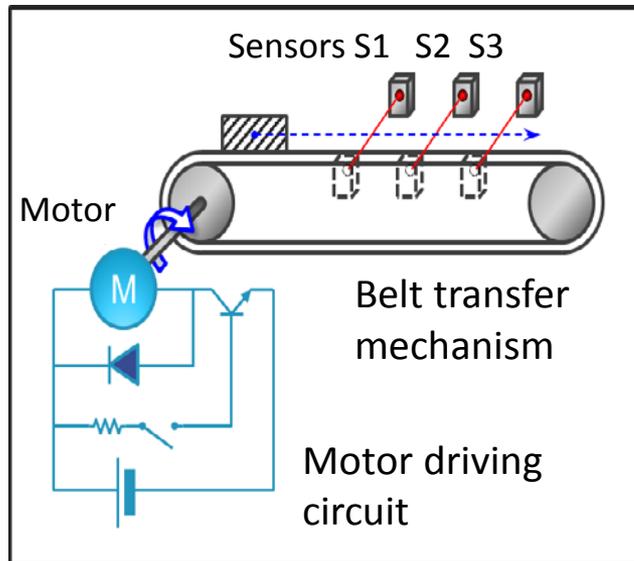
Amount of motion (m)



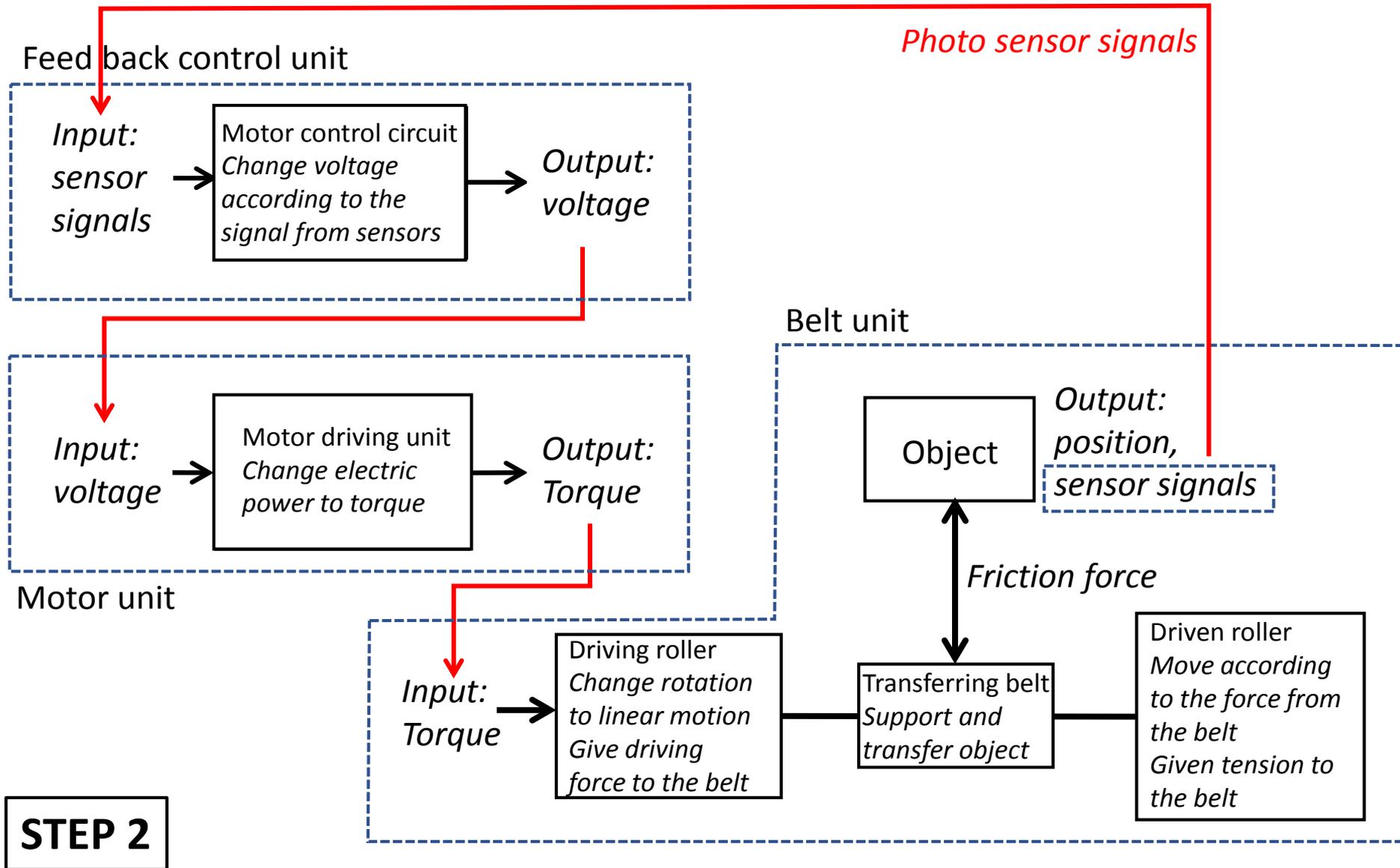
# CASE 2 Belt transfer mechanism with sensors

1. When the power is turned on, the driving motor rotates at speed M0.
2. When the object passes in front of the light blocking sensor at S1, the speed of the drive motor is switched from M0 to M1.
3. When the object is further conveyed and passed in front of the light blocking sensor at S2, the speed of the driving motor is switched from M1 to M2.
4. When the object is further transported and passed in front of the light blocking sensor S3, the speed of the drive motor is switched from M2 to M0.

**STEP 1**

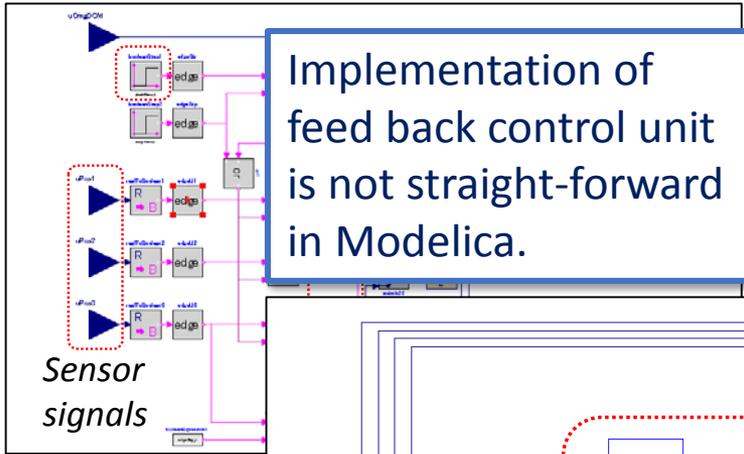


# Block diagram of the belt transfer mechanism

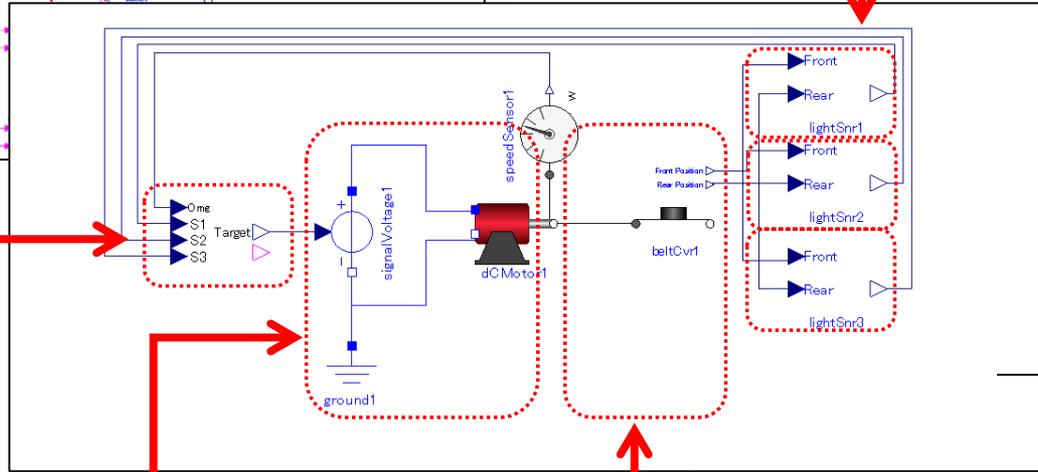
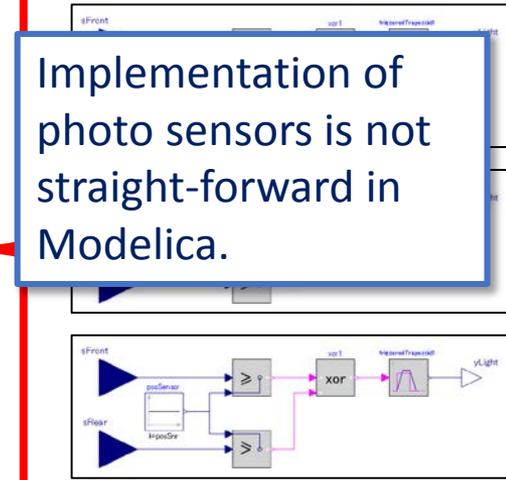


# A belt transfer model in Modelica

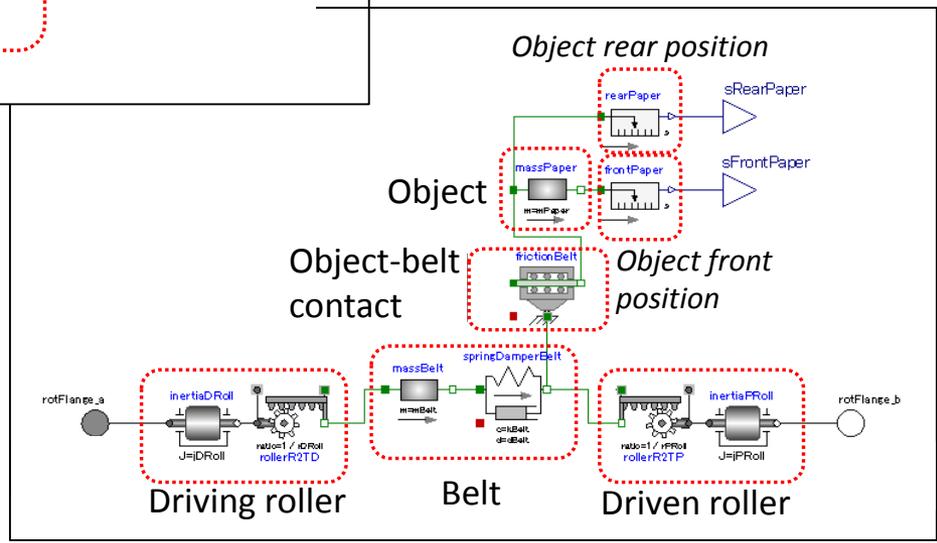
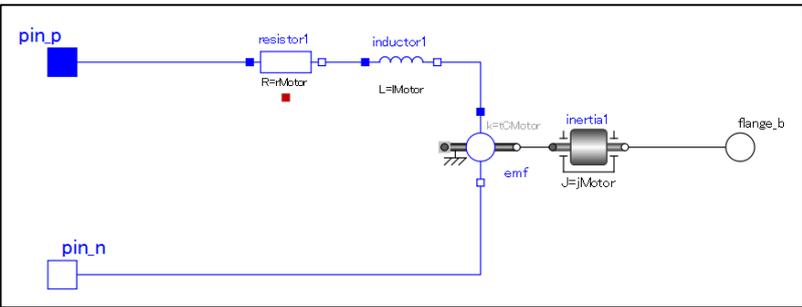
Feed back control unit



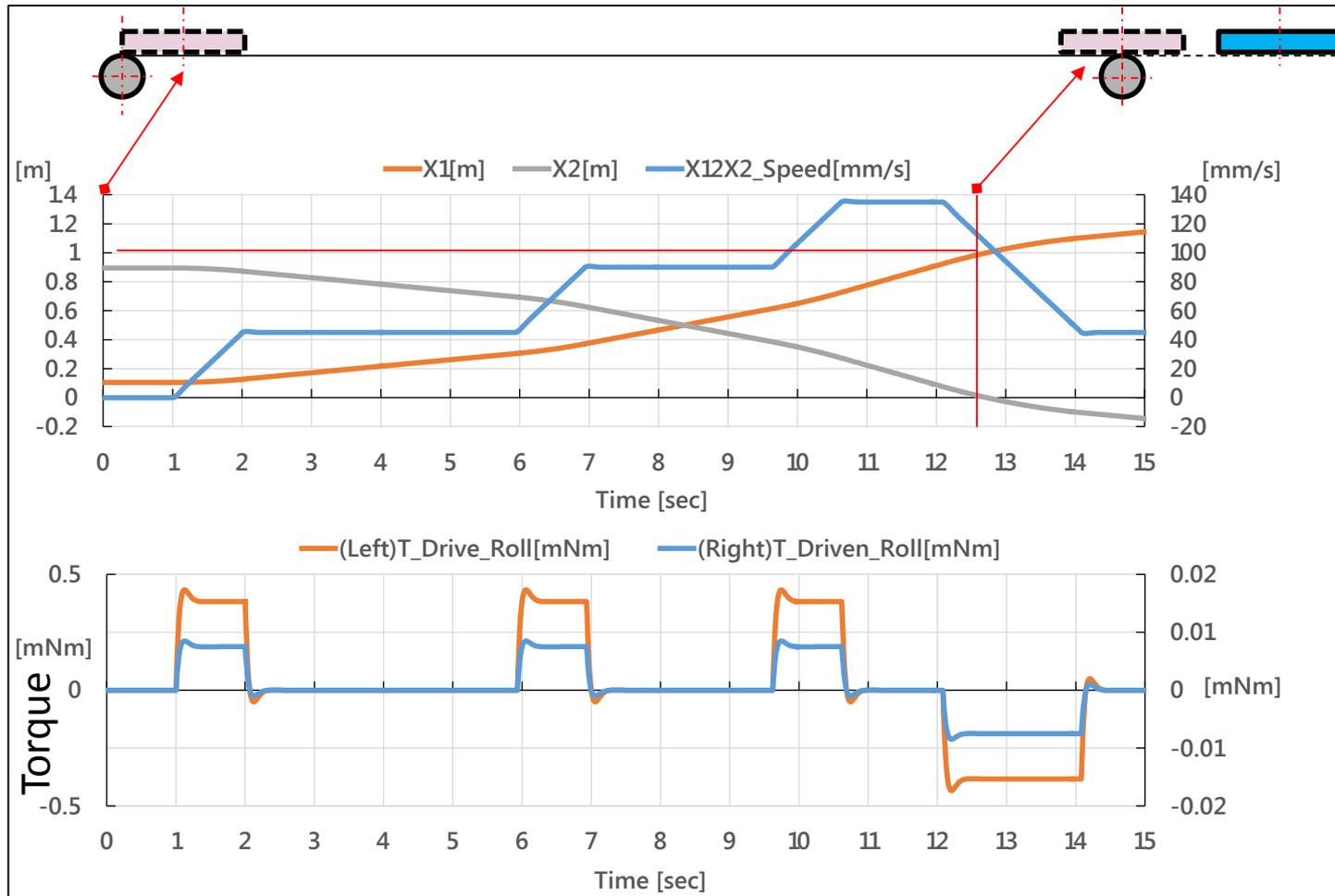
Sensors



**STEP 3**



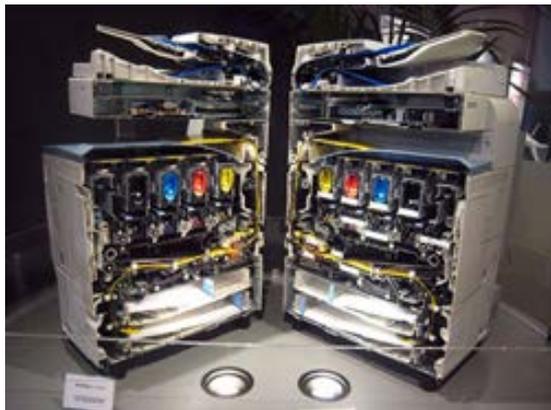
# Simulation result



# Necessary components in Modelica library for supporting mechano-electrical product design



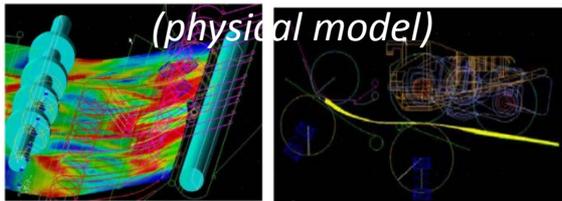
- Modelica Standard Library (MSL) was used in our empirical study for maintaining the model compatibility.
- Components of the MSL are not sufficient for constructing a practical model.
  - In the mechano-electrical product, it is necessary to represent switching mechanisms with sensors; however, they are not prepared in MSL.
- Examples of models not supported in MSL.
  - Motion model of charged toner powder in the electrophotographic process.
  - Heat transfer model considering spatial distribution.
  - Frequency/temperature-dependent viscoelastic model.
  - Model of aerodynamic force acting on paper.
  - Vibration, impact, and noise.



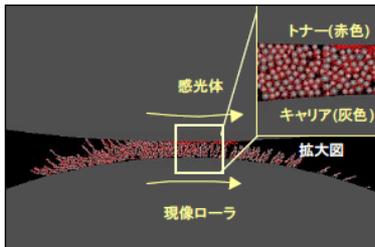
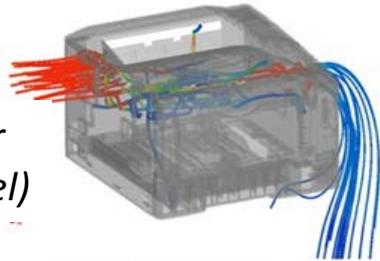
# Necessity of co-simulation with FMI

- For each component of a copier, a different simulation method specialized for each function is used.
  - Analysis of paper transfer, exposure, line image generation, development, image transfer, fixing.
  - Simulation of development, image transfer, and fixing must analyze the complex behavior of toner particles in 3D space. A statistical model is used for reducing computation time.
- Function analysis must be performed on components simultaneously so that trade-offs between components can be evaluated in the early design stage. Co-simulation with FMI is much expected.

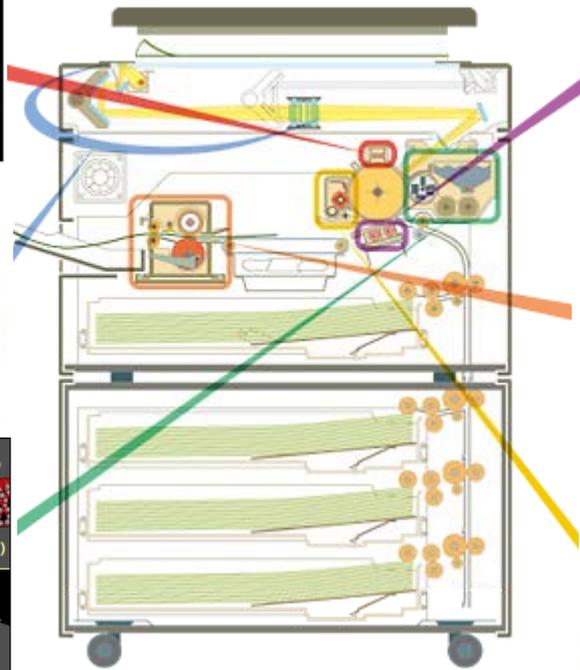
Paper-transfer system



Heat transfer (physical model)



Development (statistical model)



Multifunctional copier

Image transfer with toner particles (statistical model)

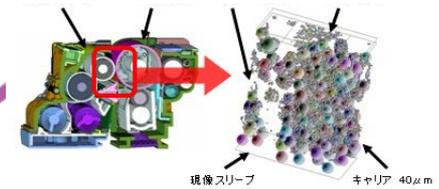
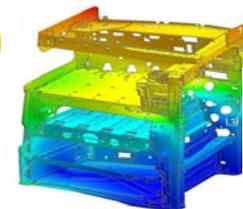
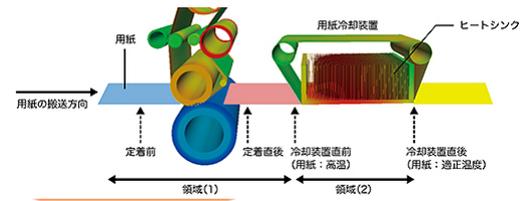


Image fixing (statistical model)



Chassis and frame (physical model)

# Check table of requirements of new digital verification technology and Modelica

Requirements	Result	Comments based on the empirical study
Simulation in early design stage	○	<ul style="list-style-type: none"> <li>Users can build models of representative mechanism of the mechano-electrical product by simply connecting pre-defined component models in the display.</li> </ul>
Description of physical phenomena in multiple domains (electrical, mechanical, optical, and software)	○	<ul style="list-style-type: none"> <li>The collaborative use of mechanical system models and electric system models was successful in our empirical study with Modelica, however switching mechanisms with sensors are not easily implemented.</li> <li>There are some examples of the collaborative uses of Modelica-MATLAB/Simulink and SystemC for software development.</li> </ul>
Formalization of know-hows	△	<ul style="list-style-type: none"> <li>Know-hows in early design stages can be described with Modelica, however additional systems are necessary for properly managing the know-hows.</li> </ul>
Description of justification of decisions	△	<ul style="list-style-type: none"> <li>Justifications can be described in Modelica, however additional systems are necessary for properly managing the justifications.</li> </ul>
Building company-specific models	○	<ul style="list-style-type: none"> <li>Good understanding of the physical phenomena related to a product's function and sufficient knowledge of the component models prepared in the Modelica library is necessary.</li> <li>Some companies provide good educational course and materials for model construction.</li> </ul>
Confidentiality maintenance	△	<ul style="list-style-type: none"> <li>By using FMI, the computation process in a model can be concealed. Reliability assurance of the supplied model in FMI is uncertain.</li> </ul>
Cooperation with 3D CAD/CAE	△	<ul style="list-style-type: none"> <li>During our empirical study, integration of 1D CAE and 3D CAD systems had not yet been evaluated. Few case studies of co-simulations with 1D CAE and 3D CAE are known. This issue is still in a research phase.</li> </ul>

# Conclusions

- Simulation technology for assisting activities in the early design stage of the precision mechano-electrical product is necessary.
- Use of 1D CAE is promising because;
  - 1D CAE can support both mechanical systems and electrical systems.
  - It is applicable in the conceptual and functional design stage where 3D information is not determined.
- To promote the use of 1D CAE in the mechano-electrical industry, modeling guideline is proposed.
- To evaluate the applicability of the guideline, we conducted some empirical studies of the modeling.
  - The collaborative use of mechanical system models and electric system models was successful in our empirical study, however implementation of some mechanisms (e.g. switching mechanism with sensors) was not easy.
- Supporting of the co-simulation of various simulation systems is necessary for realizing total simulation of the mechano-electrical product.

# Future direction for standardization

- Modelica, FMI, MATLAB/Simulink are still in a development stage. Future specification changes and technology changes are unavoidable. Standardization should be done in “de facto standard” way.
- In the MBD field, effort for the standardization is mainly done in each industry associations.
- In the automobiles/aircrafts industry, global cooperation is in progress. On the other hand, efforts for the global cooperation is not known in the mechano-electrical industry.
- FMI is an important linkage for co-simulation and model exchange. Standard framework for good combined use of Modelica-MATLAB/Simulink-SystemC (for software) is a key.

