# Key maturity indicators for module libraries for PLC-based control software in the domain of automated Production Systems

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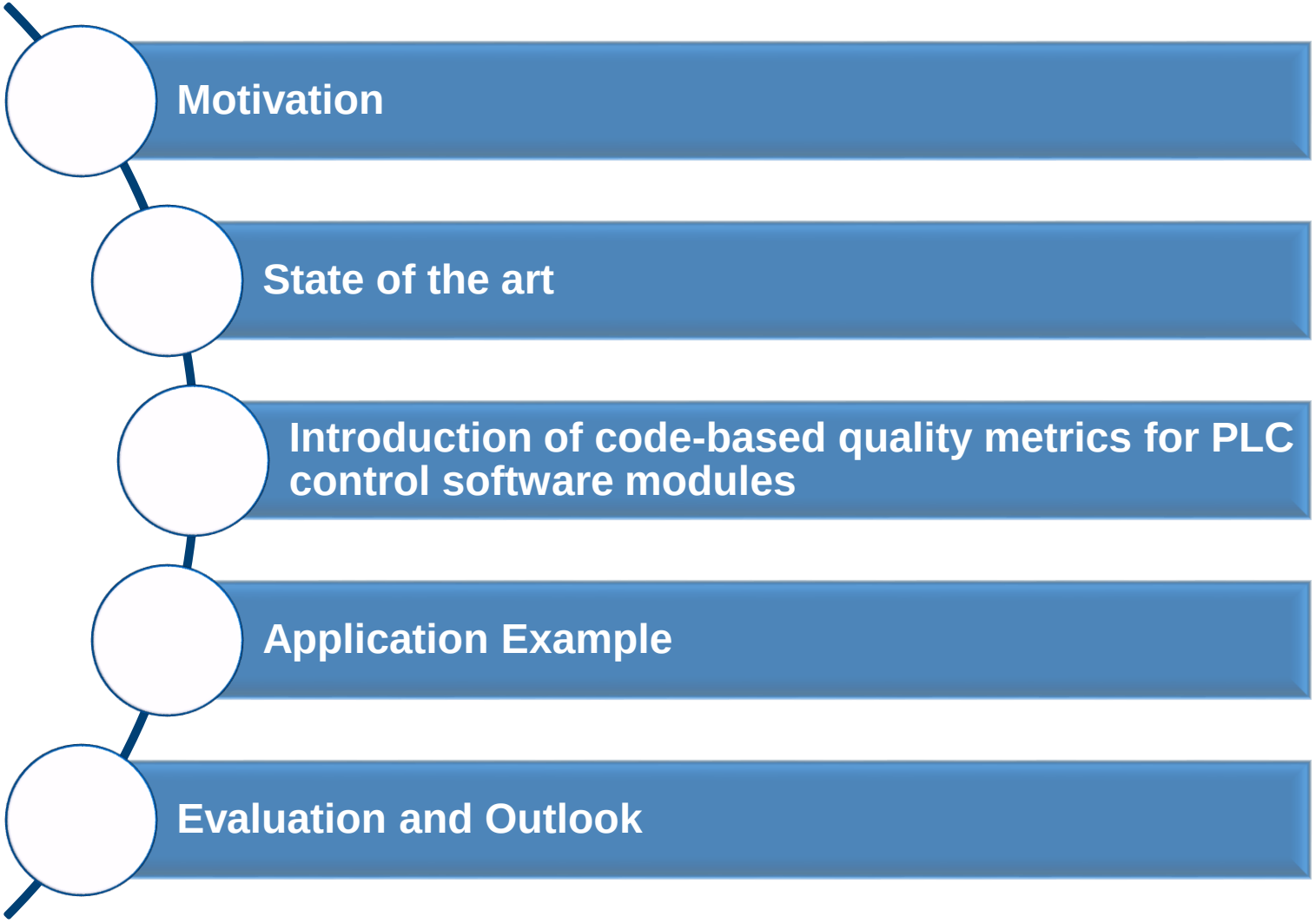
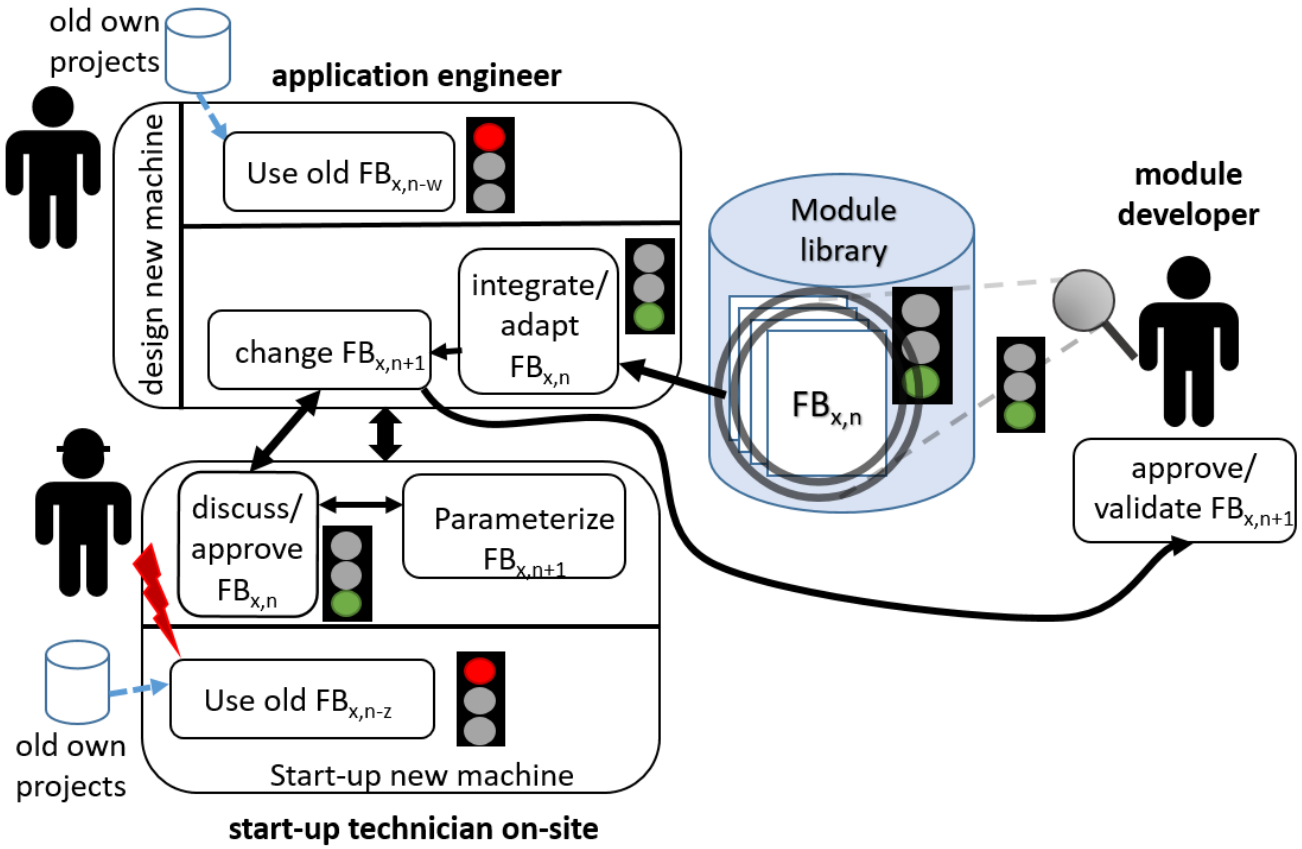
# Agenda



# Motivation for maturity metrics for control software module libraries

## Workflow of library module development



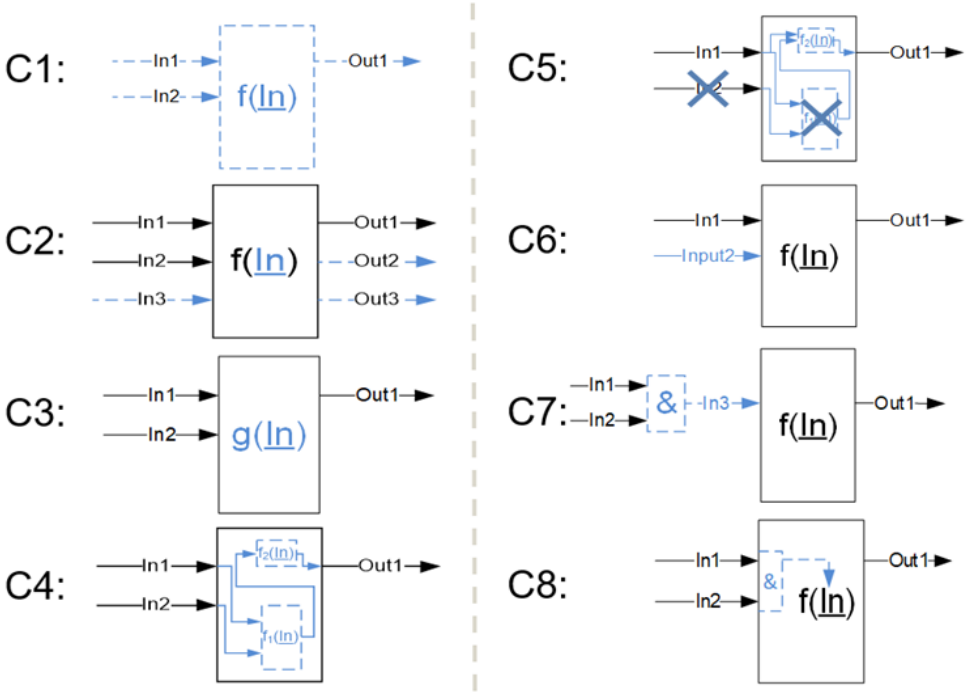

**1.) High maturity:**
**Green traffic light**

**2.) Medium maturity:**
**Yellow traffic light**

**3.) Low maturity:**
**Red traffic light**

# State of the art in mature PLC-based control software module evolution

- **Classification of changes / evolution in PLC code**



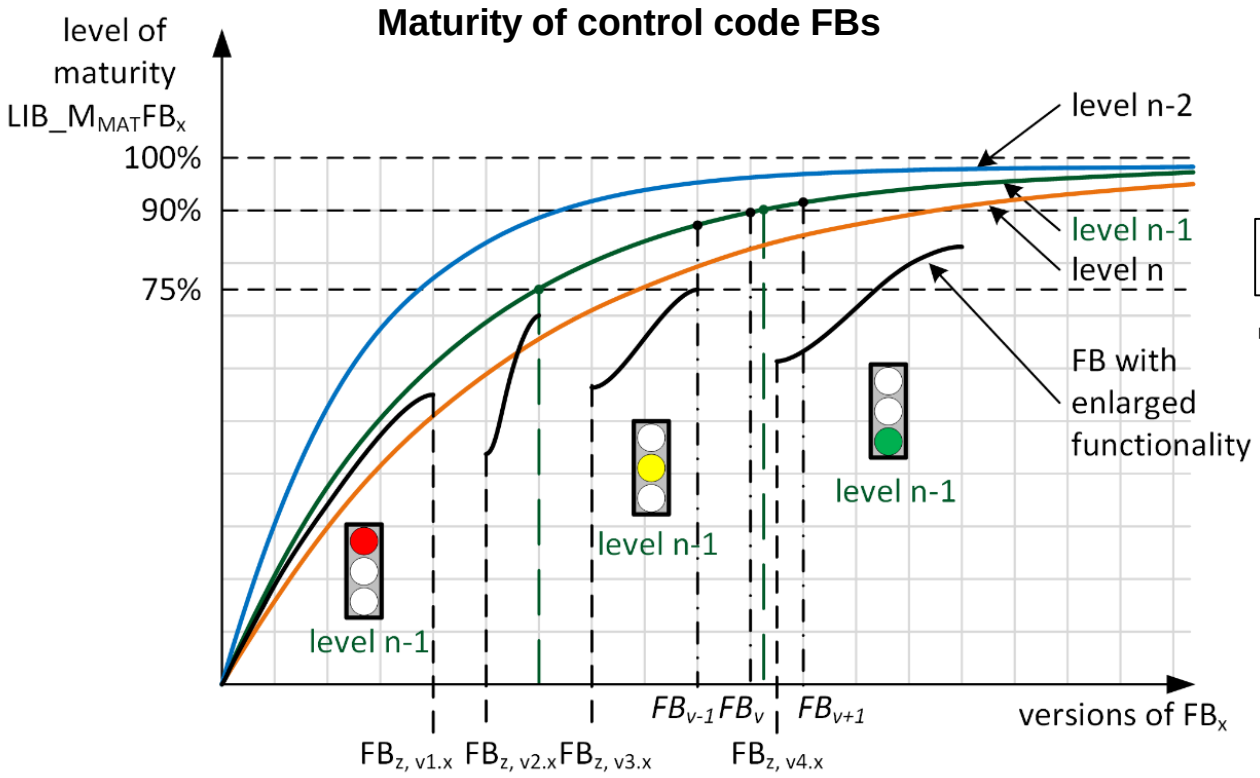

$IM_{C1}, IM_{C2} > IM_{C3}$ and $IM_{C4} > IM_{C5}$ and $IM_{C7} > IM_{C6}$

Extended classification of Vogel-Heuser et al. (2014) of possible changes of a FB in IEC 61131-3 and comparison of the respective impacts IM on module maturity rated by industrial application experts

- **Code analysis for PLC code**
  - Questionnaire and code analysis of industrial legacy control code (Vogel-Heuser et al. (2017)) confirmed applicability of **Halstead program length** and **McCabe's complexity** to PLC languages (Capitán et al. (2017))

- **Code-based software quality metrics in general software engineering**
  - Hristov et al. (2012): structuring of reuse metrics into availability, documentation, complexity, quality, maintainability and adaptability
  - Deniz et al. (2014): code-based quality metrics in industrial settings (quality of software products is improved as reuse rates of the product increases)

# Code-based quality metrics for PLC control software modules




$$\Delta FB_{v+1} < \Delta FB_{v} < \Delta FB_{v-1} \quad (1)$$

- Changes decrease with a rising version number indicating a higher maturity level of the FB

$$\Delta FB_{x,Operation} < \Delta FB_{x,Start-up} < \Delta FB_{x,Design} \quad (2)$$

- Changes to one specific $FB_x$ decrease as it advances in the software engineering life cycle

$$\Delta FB_{x,level} > \Delta FB_{x,level-1} > \Delta FB_{x,level-2} \quad (3)$$

- Maturity of a $FB_{x,level-2}$ from a lower level of the software architecture is higher than the one of a higher level $FB_{x,level-1}$

# Code-based quality metrics for PLC control software modules

## Maturity metrics for evolving FBs in a module library

$$LIB\_M_{Mat}FB_x = 1 - \frac{1}{n} \cdot \sum_{y=1}^{n} \Delta FB_{x,y} = 1 - \frac{1}{n} \cdot$$

$$\left( \frac{|n_A \cdot k_{AI}| + |n_D \cdot k_{DI}| + |n_C \cdot k_{CI}| + |m_A \cdot k_{AO}| + |m_D \cdot k_{DO}| + |m_C \cdot k_{CO}|}{|I_A \cdot k_{AI}| + |I_D \cdot k_{DI}| + |I_C \cdot k_{CI}| + |O_A \cdot k_{OA}| + |O_D \cdot k_{DO}| + |O_C \cdot k_{KO}|} \right.$$

$$+ \left| \frac{\Delta variables}{\sum variables} \right| + \left| \frac{\Delta interface\ changes}{\sum interface\ elements} \right| + \left| \frac{\Delta calls}{\sum calls} \right|$$

$$+ \left| \frac{\Delta adaption\ of\ module\ implementation}{\sum module\ implementations} \right|$$

$$+ \left| \frac{\Delta adding/deleting\ of\ sub-modules}{\sum sub-modules} \right|$$

$$+ \left| \frac{\Delta adding/deleting\ of\ preprocessing\ of\ inputs\ external}{\sum preprocessing\ of\ inputs\ external} \right|$$

$$\left. + \left| \frac{\Delta changed\ designations}{\sum variables} \right| \right)$$

(4)

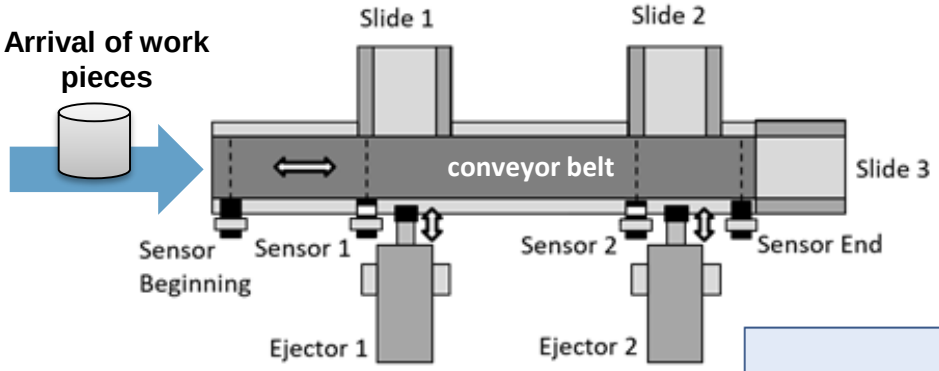
With: $n = number\ of\ \Delta FB \wedge \Delta FB \neq 0$

| | |
|---|---|
| $n_A$ | number of changed analogue inputs $I_A$ |
| $k_{AI}$ | Weighting factor for analogue inputs |
| $n_D$ | number of changed digital inputs $I_D$ |
| $n_C$ | number of changed counter inputs $I_C$ |
| $m_A, m_D, m_C$ | respective changes of the outputs O |
| $k$ | Weighting factors |

$$LIB\_M_{Mat}FB_x = \begin{cases} 1 & if\ nothing\ is\ changed \\ 0 & if\ everything\ is\ changed \\ > 0 \wedge < 1 & in\ case\ of\ changes \end{cases}$$

(5)

# Application of the proposed metrics




**FB_Conveyor_Sc10**

| | |
|---|---|
| DI_Sensor_1 BOOL | BOOL DO_TurnClockwise |
| DI_Sensor_2 BOOL | BOOL DO_TurnCounterclockwise |
| DI_Sensor_End BOOL | BOOL DO_Extend_Ejector_1 |
| DI_Sensor_Beginning BOOL | BOOL DO_Extend_Ejector_2 |
| t_evacuate_time TIME | BOOL b_initialized |
| | BOOL b_WP_passed_End |
| | BOOL b_WP_started |
| | BOOL b_TurningClockwise |
| | BOOL b_TurningCounterclockwise |

**1) Original specific FB**

**FB_Conveyor_4**

| | |
|---|---|
| DO_TurnClockwise BOOL | BOOL b_TurningClockwise |
| DO_TurnCounterclockwise BOOL | BOOL b_TurningCounterclockwise |
| DI_Sensor_1 BOOL | BOOL b_Engine_Stopped |
| DI_Sensor_2 BOOL | BOOL b_initialized |
| DI_Sensor_3 BOOL | BOOL b_WP_started |
| DI_Sensor_4 BOOL | BOOL b_WP_passed_End |
| DI_Sensor_5 BOOL | BOOL b_Check_WP_passed_END |
| DI_Sensor_END BOOL | |
| DI_Sensor_Beginning BOOL | |
| fb_Ejector_1 FB_Ejector | |
| fb_Ejector_2 FB_Ejector | |
| fb_Ejector_3 FB_Ejector | |
| fb_Ejector_4 FB_Ejector | |
| fb_Ejector_5 FB_Ejector | |
| fb_Slide_Sliding_film_1 FB_Slide_Sliding_film | |
| fb_Slide_Sliding_film_2 FB_Slide_Sliding_film | |
| fb_Slide_Sliding_film_3 FB_Slide_Sliding_film | |
| fb_Slide_Sliding_film_4 FB_Slide_Sliding_film | |
| fb_Slide_Sliding_film_5 FB_Slide_Sliding_film | |
| b_TurnClockwise BOOL | |
| b_TurnCounterclockwise BOOL | |
| b_Stop_Conveyor BOOL | |
| t_evacuate_time TIME | |
| b_start_Beginning_CW BOOL | |
| b_start_Beginning_CCW BOOL | |
| b_DO_Check BOOL | |
| b_stop_END BOOL | |
| t_overrun_time TIME | |

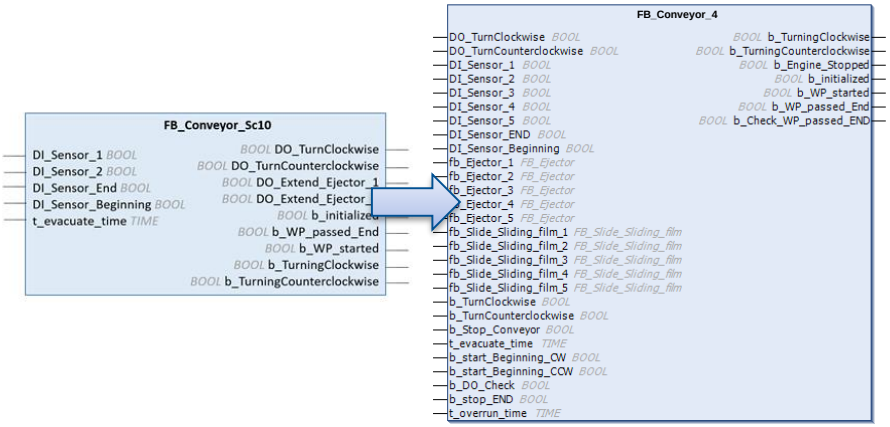
**2) General FB**

# Application of the proposed metrics

## Specific FB → General FB

- The original FB comprises 14 interfaces whereas the adapted FB has 35 interface elements:

$$FB_{1.x,1} = \left| \frac{\Delta interface\ changes}{\sum interface\ elements} \right| = \left| \frac{14-35}{35} \right| = 0.60$$




- The original FB implementation comprises 47 LOC and 87 LOC were adapted, which means that they were either added, removed or edited:

$$FB_{1.x,2} = \left| \frac{\Delta Module\ implementations}{\sum Module\ implementations} \right| = \left| \frac{47-87}{87} \right| \approx 0.46$$

Excerpt from the Original FB

```
21  END_IF
22
23  //Emergency Stop
24  IF b_emergency_stop THEN
25      b_Stop_Conveyor := TRUE;
26      b_TurnClockwise          :=FALSE;
27      b_TurnCounterclockwise   :=FALSE;
28      b_initialized := FALSE;
29  END_IF
```

```
29  END_IF
30
31  //Emergency Stop
32  IF b_emergency_stop THEN
33      fb_engine_conveyor.ACT_Stop_Engine();
34      b_initialized := FALSE;
35  END_IF
```

Excerpt from the Optimized FB

# Application of the proposed metrics

## Specific FB → General FB

- The original FB comprises 14 interfaces whereas the adapted FB has 35 interface elements:

$$FB_{1.x,1} = \left| \frac{\Delta interface\ changes}{\sum interface\ elements} \right| = \left| \frac{14-35}{35} \right| = 0.60$$

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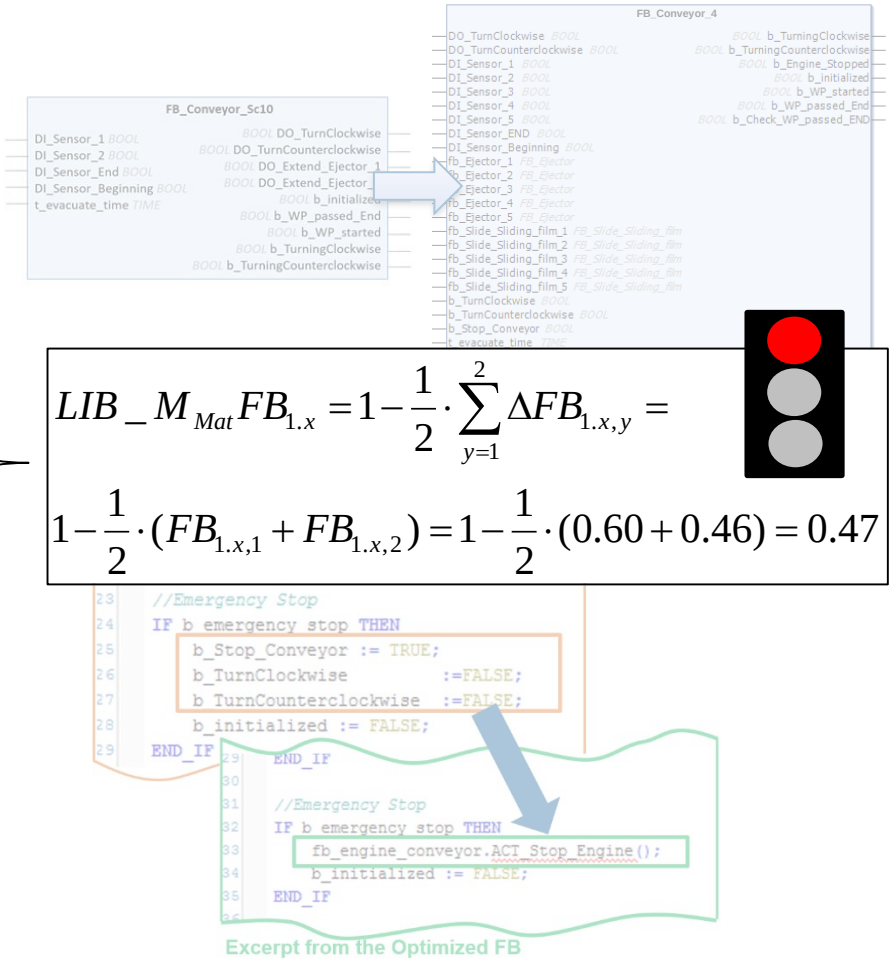


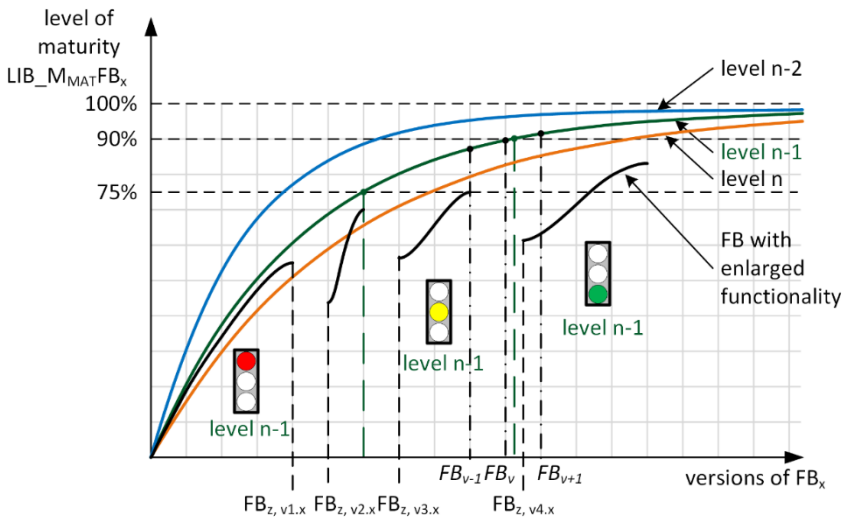

$$LIB\_M_{Mat}FB_{1.x} = 1 - \frac{1}{2} \cdot \sum_{y=1}^{2} \Delta FB_{1.x,y} =$$

$$1 - \frac{1}{2} \cdot (FB_{1.x,1} + FB_{1.x,2}) = 1 - \frac{1}{2} \cdot (0.60 + 0.46) = 0.47$$

# Previous feedback and outlook

## Qualitative evaluation by industrial experts

- All experts agreed on the exponential behavior:




- The terms of (4) may need **refinement**, but the rationale was **accepted** by all of them.

$$LIB\_M_{Mat}FB_x = 1 - \frac{1}{n} \cdot \sum_{y=1}^{n} \Delta FB_{x,y} = 1 - \frac{1}{n} \cdot \left( \frac{|n_A \cdot k_{AI}| + |n_D \cdot k_{DI}| + |n_C \cdot k_{CI}| + |m_A \cdot k_{AO}| + |m_D \cdot k_{DO}| + |m_C \cdot k_{CO}|}{|I_A \cdot k_{AI}| + |I_D \cdot k_{DI}| + |I_C \cdot k_{CI}| + |O_A \cdot k_{OA}| + |O_D \cdot k_{DO}| + |O_C \cdot k_{KO}|} + \left| \frac{\Delta variables}{\sum variables} \right| + \left| \frac{\Delta interface\ changes}{\sum interface\ elements} \right| + \left| \frac{\Delta calls}{\sum calls} \right| + \left| \frac{\Delta adaption\ of\ module\ implementation}{\sum module\ implementations} \right| + \left| \frac{\Delta adding/deleting\ of\ sub-modules}{\sum sub-modules} \right| + \left| \frac{\Delta adding/deleting\ of\ preprocessing\ of\ inputs\ external}{\sum preprocessing\ of\ inputs\ external} \right| + \left| \frac{\Delta changed\ designations}{\sum variables} \right| \right) \quad (4)$$

**Outlook:**

- Adaption of the metrics to **other IEC 61131-3 programming languages**
- Introduction of **weighting factors**
- Evaluation of the metrics using **industrial PLC code**

# Thank you very much for your attention!

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