SMART PRODUCTION SYSTEMS:
THEORETICAL FOUNDATIONS, COMPUTATIONAL TOOLS, and PRACTICAL DESIGN

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OUTLINE

1. SPS Definition and Architecture
2. Production System Types and *PSE Toolbox*®
3. IU: Theoretical Foundation and Computational Tools
4. AU: Theoretical Foundation and Computational Tools
5. OU: Theoretical Foundation and Computational Tools
6. SPS AT: Architecture, Design, Operation, and Verification
7. Concluding Remarks

1 SPS Definition and Architecture

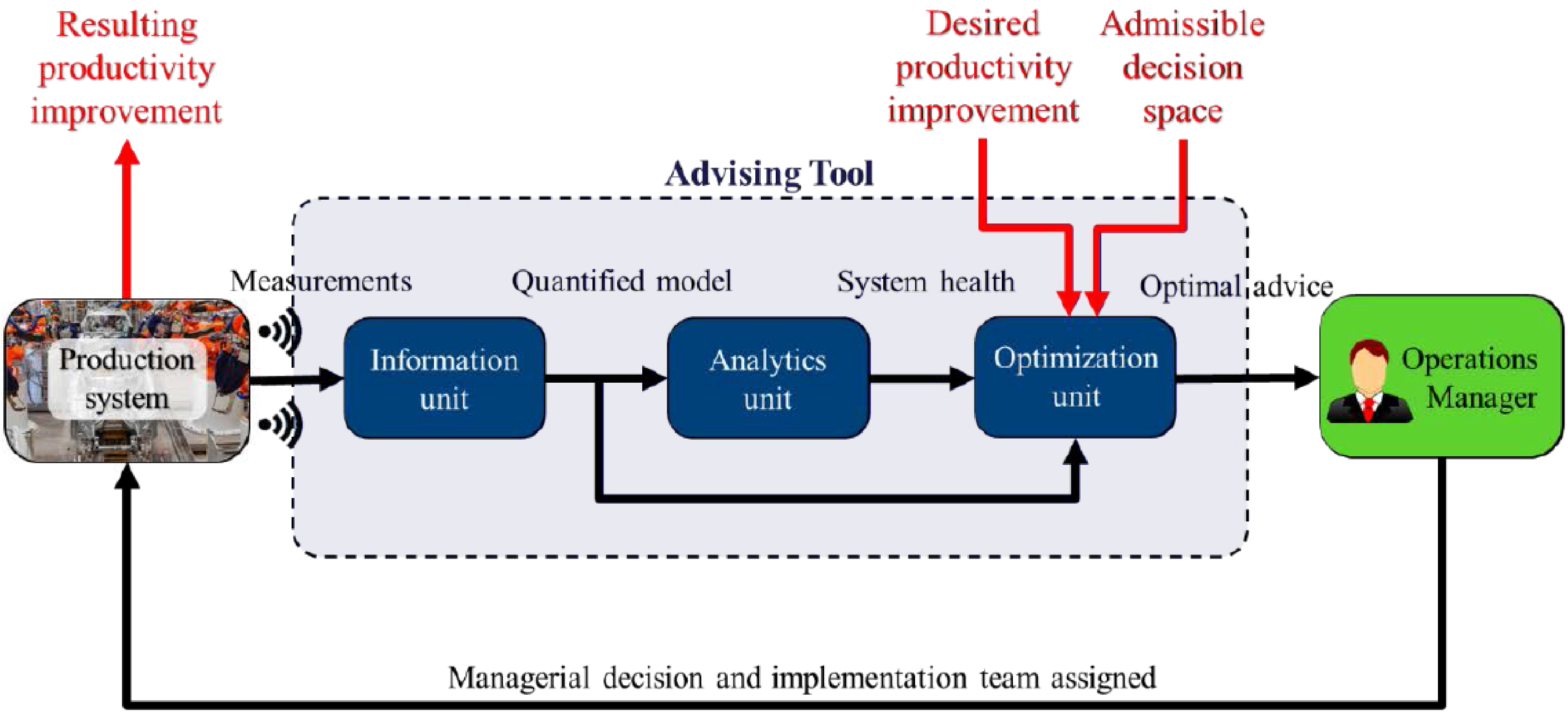
- **Smart Production Systems** (SPS) – production systems capable of self-diagnosing and designing optimal continuous improvement projects, leading to the desired productivity improvement.
- SPS may operate in two modes – *semi-autonomous* and *autonomous*.
  - Semi-autonomous: The SPS computes the optimal advice, while the Operations Manager authorizes its implementation (manager-in-the-loop)
  - Autonomous: The SPS-designed continuous improvement project is autonomously authorized for implementation.
- The current work addresses the semi-autonomous regime.

1 SPS Definition and Architecture (cont)

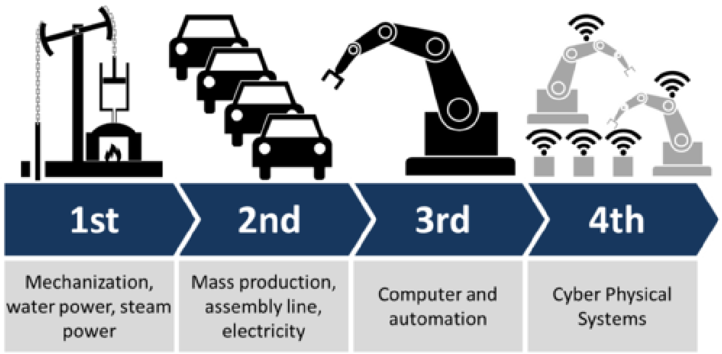
- To be "smart", a production system must be equipped with an *Advising Tool* (AT) consisting of:
  - *Information Unit* (IU)
  - *Analytics Unit* (AU)
  - *Optimization Unit* (OU)
- IU – utilizes sensing/computing/communication devices (e.g., Industry 4.0 technology) to monitor performance metrics.
- AU – utilizes the theory of Production Systems Engineering (PSE) in order to analyze system's health and investigate various "what if" scenarios of potential improvement.
- OU – utilizes methods of Artificial Intelligence to select the optimal advice for achieving the desired productivity improvement (if at all possible).

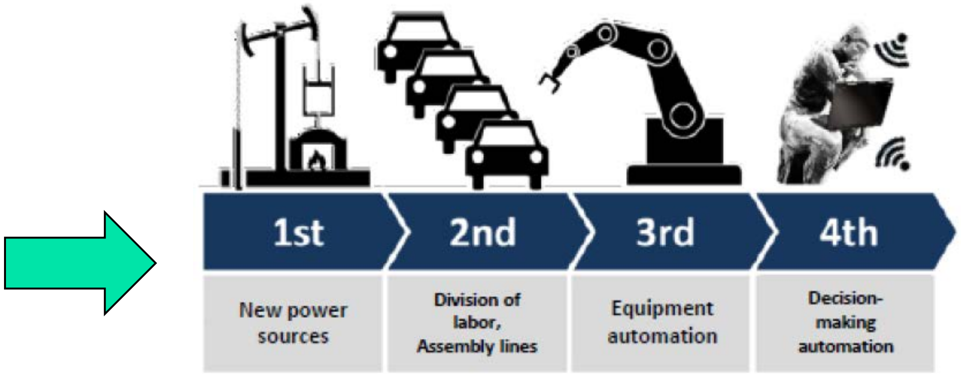
1 SPS Definition and Architecture (cont)

- SPS architecture, developed in this work is as follows:



- **SPS connection with Industry 4.0**





  - SPS contributes to automation of decision-making processes.
  - SPS could be viewed as a part of a major concept of Industry 4.0 – *Smart Factory*.

1 SPS Definition and Architecture (cont)

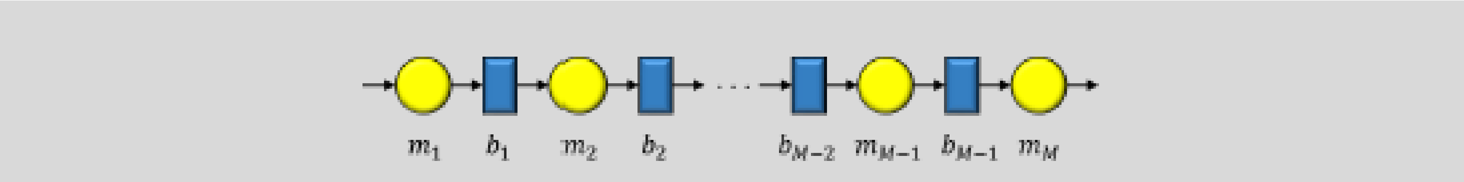
- **SPS connection with Control Theory**
  - Major concepts of control:
    - Plant – system to be automated (e.g., a boiler at power plant)
    - Sensors – devices to monitor process variables (e.g. temperature)
    - Reference signal – the desired values of process variables
    - Controller – algorithm for calculating appropriate plant inputs
    - Actuators – devices to actuate process variables.
  - Major concepts of SPS:
    - Plant – production system
    - Sensors – PLC and others performance monitoring devices
    - Reference signal – the desired productivity improvement
    - Controller – SPS Advising Tool
    - Actuator – Operations Manager and improvement project implementation team.

1 SPS DEFINITION AND ARCHITECTURE (CONT)

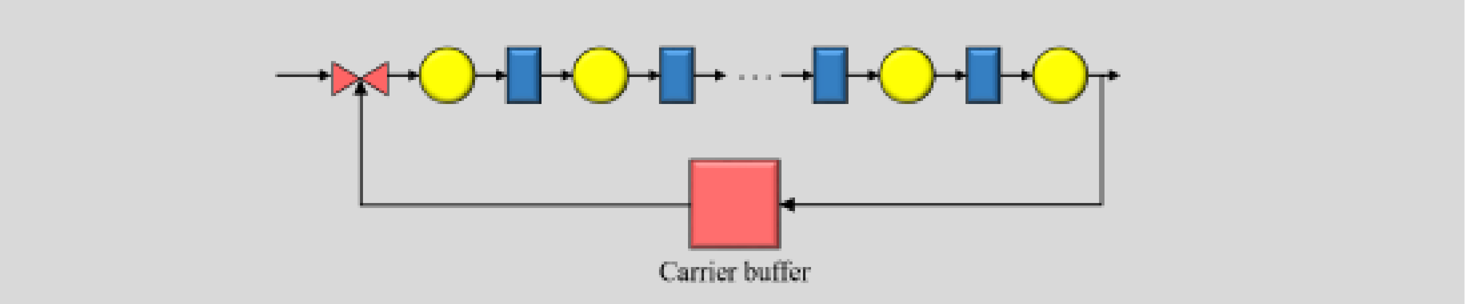
- SPS connection with Control Theory (cont)
  - Similar to control systems, designing SPS requires a process consisting of:
    - Developing a model of the production systems at hand
    - Designing Information Unit
    - Designing Analytics Unit
    - Designing Optimization Unit
    - Designing the structure and format of the advice to the Operations Manager.
  - Also similar to control systems, this process may take a relatively long period of time before full functionality of SPS is reached.
- This talk is intended to outline major steps of this development process.

2 Production System Types and *PSE Toolbox*

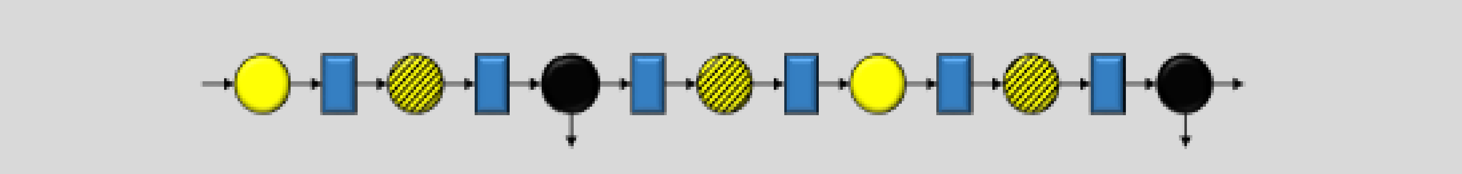
- **Types of production systems considered:**
  - Serial lines



  - Closed serial lines

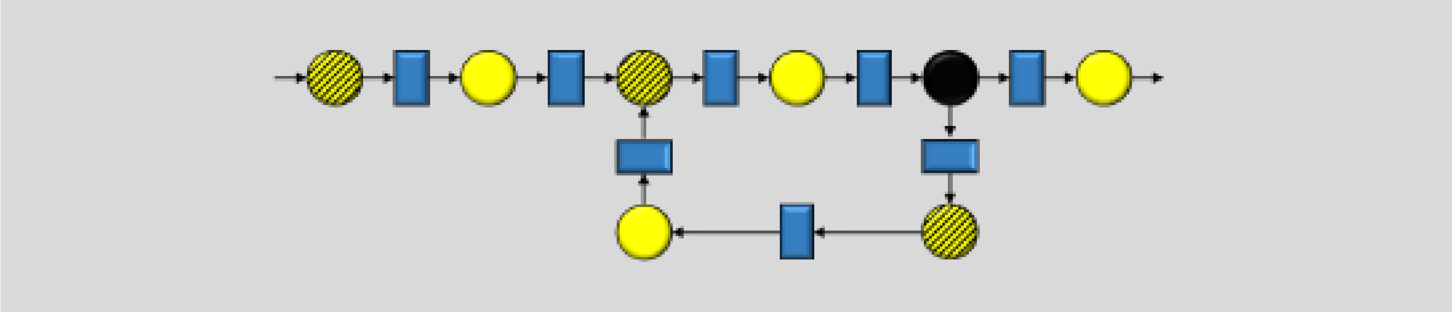


  - Serial lines with product quality inspection

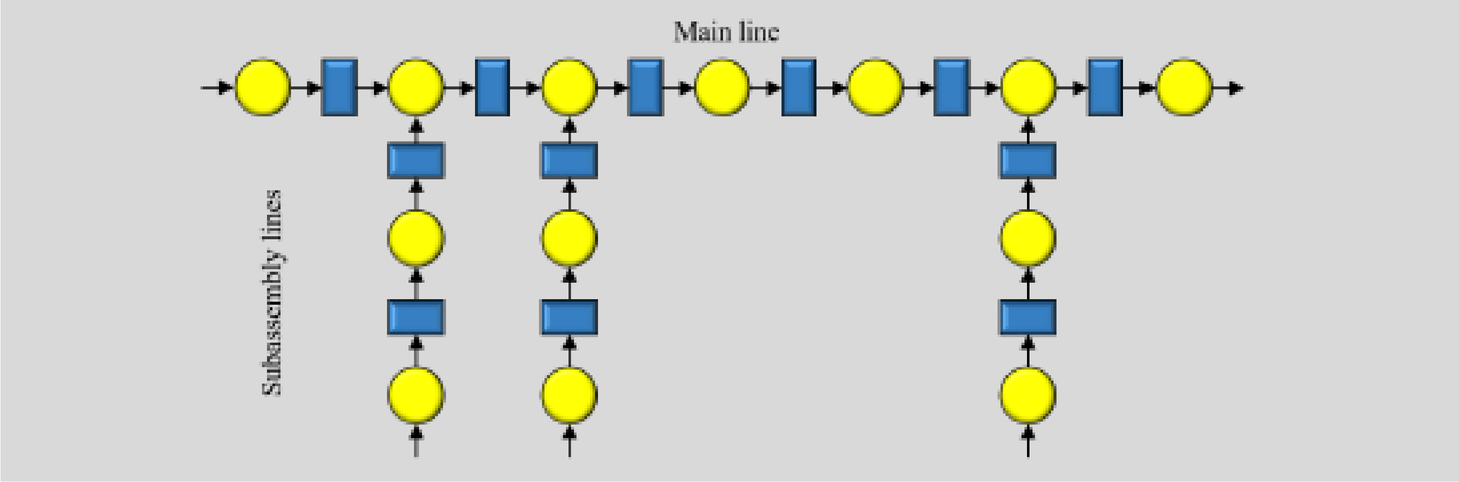


2 PRODUCTION SYSTEM TYPES AND *PSE TOOLBOX* (CONT)

- Types of production systems considered (cont):
  - Serial lines with re-work

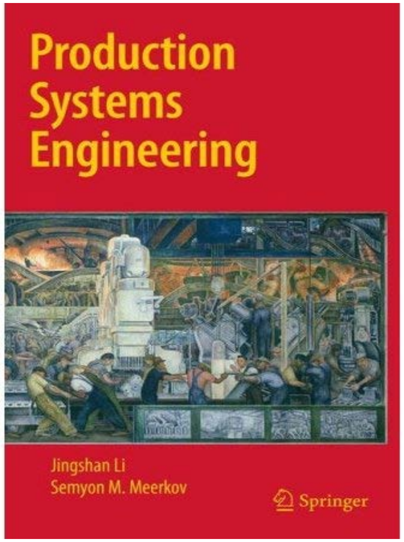


  - Assembly systems



2 PRODUCTION SYSTEM TYPES AND *PSE TOOLBOX* (CONT)

- Performance metrics of importance:
  - Throughout (TP)
  - Work-in-process (WIP)
  - Probabilities of blockage and starvation (BL and ST)
  - Production lead time (LT)
- Analytical methods for their evaluation have been developed in J. Li and S.M. Meerkov, *Production Systems Engineering*, Springer 2009 (in Chinese, 2011).
  - While PSE uses standard terms, such as *bottlenecks*, *leanness*, *lead time*, etc., it infuses them with rigorous quantitative meaning and provides analytical formulas for their evaluation.



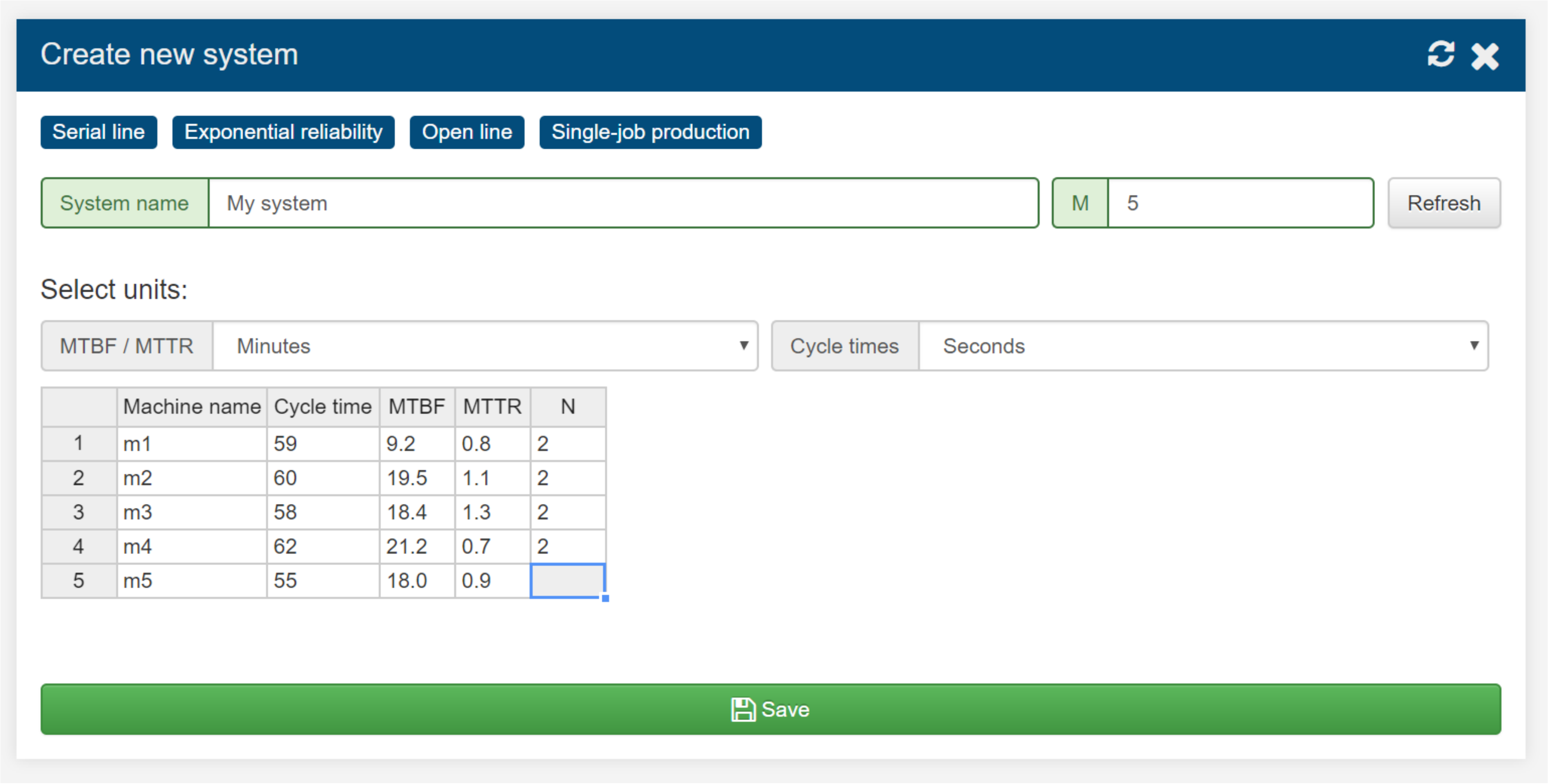
- To facilitate applications, we developed a web-based *PSE Toolbox*®
- **These methods and tools allow to make a production system "smart".**

2 Production System Types and *PSE Toolbox* (cont)

- ***PSE Toolbox***® **architecture** (home page):

2 Production System Types and *PSE Toolbox* (cont)

- The process of *PSE Toolbox*® utilization begins with "Create a new system" (or "Selecting existing" system):



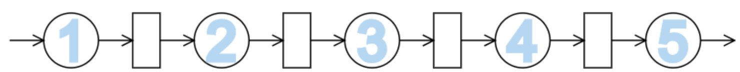
	Machine name	Cycle time	MTBF	MTTR	N
1	m1	59	9.2	0.8	2
2	m2	60	19.5	1.1	2
3	m3	58	18.4	1.3	2
4	m4	62	21.2	0.7	2
5	m5	55	18.0	0.9	

2 Production System Types and *PSE Toolbox* (cont)

- Then, various *PSE Toolbox*® modules can be applied:
  - For example, using “Performance analysis” module, we obtain:

ACTIVE SYSTEM: My system | You | Create new system | Select existing system | Select shared system | Select example

Performance analysis



Machine name	m1		m2		m3		m4		m5
Cycle time (Seconds)	59.0		60.0		58.0		62.0		55.0
MTBF (Minutes)	9.20		19.5		18.4		21.2		18.0
MTTR (Minutes)	0.80		1.10		1.30		0.70		0.90
Efficiency	0.92		0.95		0.93		0.97		0.95
Stand-alone TP	56.1		56.8		58.0		56.2		62.3
Buffer capacity		2		2		2		2	
Starvation	0		0.025		0.051		0.034		0.13
Blockage	0.036		0.023		0.015		0.0060		0
Work-in-process		1.14		0.62		0.97		0.20	

Throughput 53.9 JPH

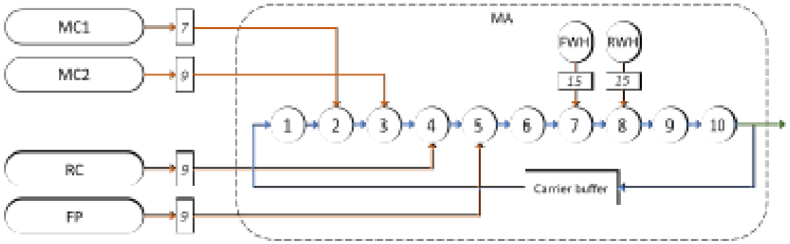
- Other *PSE Toolbox*® modules are described in subsequent sections.

3 IU: Theoretical Foundations and Computational Tools

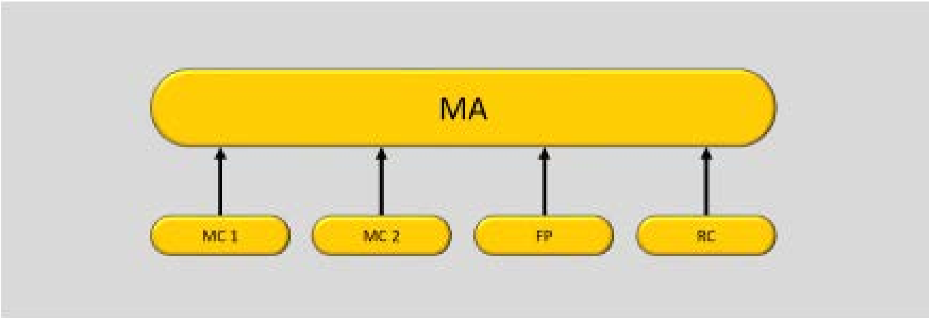
- **Theoretical foundations of IU**:
  - Theoretical foundations of IU stem from the coupling between IU and AU. This is because the model employed by AU dictates "what to measure" and "how to measure" by IU. Thus, the issue of production systems modeling is at the core of IU design.
- **Computational tools of IU**:
  - These tools are based on the algorithms for model simplification, represented in *PSE Toolbox*® by the Modeling module.
- As far as modeling is concerned, there are three types of productions system models:
  - Part flow model (PFM)
  - Mathematical model (MM)
  - Computer simulations model (CSM).

3 IU: Theoretical Foundations and Computational Tools (cont)

- **Part flow model**:
  - PFM is intended to represent *major departments* of a systems and their interconnection from the point of view of parts flow.
  - Example: Underbody assembly system:
    - Layout:

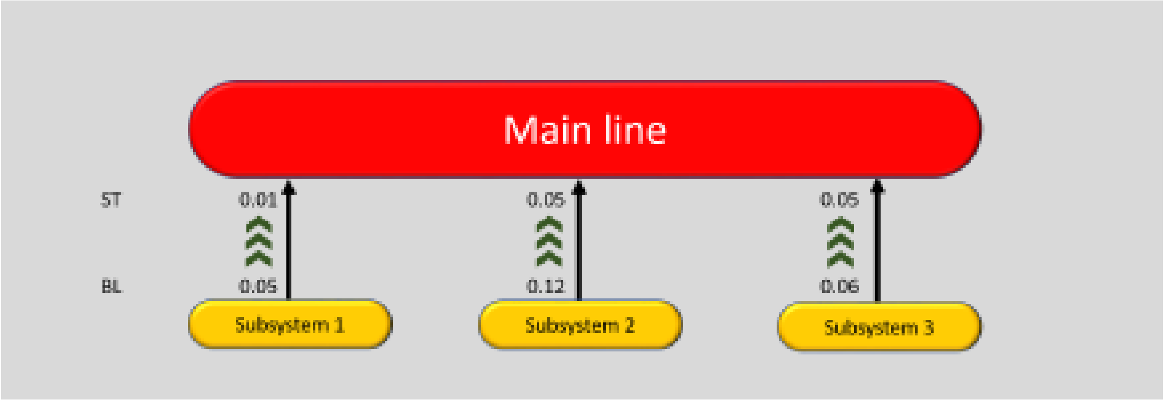


    - PFM:



3 IU: Theoretical Foundations and Computational Tools (cont)

- PFM primary utilization: BN identification based the "arrow method" developed in PSE.
- Example: Underbody assembly system:



- Thus, IU measurements in the framework of PFM must be *blockages and starvations* of production system departments.

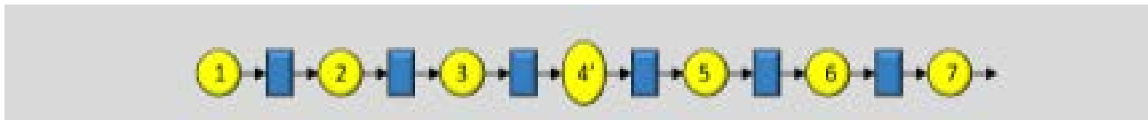
3 IU: Theoretical Foundations and Computational Tools (cont)

- **Mathematical model**:
  - MM is intended to represent production system's *simplified version, but still capturing its main features*.
  - MM consist of a block-diagram, which includes machines and buffer, along with their parameters.
  - Primary utilization: Evaluation of system's health and efficacy of "what if" continuous improvement scenarios. To carry out such calculations, PSE theory is used.
  - The process of MM development consist three steps:
    - Structural modeling
    - Parametric modeling
    - Model validation
  - Each step is repeated until the desired accuracy is achieved.

3 IU: Theoretical Foundations and Computational Tools (cont)

- IU measurements necessary for AU in the framework of MM:
  - *Machine parameters*: $\tau, T_{up}\ (MTBF), T_{down}(MTTR), BL, ST, g$
  - *System parameters* (for validation purpose): $TP, CR, WIP, LT.$
  - Using these measurements, IU calculates:
    - machine efficiency: $e = \frac{T_{up}}{T_{up}+T_{down}}$;
    - machine capacity: $c = 1/\tau$;
    - machine stand-alone throughput: $SAT = ce$.
- In addition, IU must provide information on *buffers capacities*, N_j.

- Example: LED mathematical model:
  - Structural model:



  - Parametric model:

	Op. 1	Op. 2	Op. 3	Op. 4	Op. 5	Op. 6	Op. 7
MTBF (min)	4.13	4.01	1.9	2.82	1.65	3.88	3.37
MTTR (min)	1.5	1.35	0.82	0.75	0.95	1.85	1.53
Cycle time (min)	1.1	1.05	0.98	0.87	0.92	0.95	1.05

Buffer	N_1	N_2	N_3	N_4	N_5	N_6
Capacity	4	4	4	3	3	4

  - Model validation: Average error ~2%.

Machine name	Op. 1		Op. 2		Op. 3		Op. 4		Op. 5		Op. 6		Op. 7
Cycle time (Minutes)	1.10		1.05		0.98		0.87		0.92		0.95		1.05
MTBF (Minutes)	4.13		4.01		1.90		2.82		1.65		3.88		3.37
MTTR (Minutes)	1.50		1.35		0.82		0.75		0.95		1.85		1.53
Efficiency	0.73		0.75		0.70		0.79		0.63		0.68		0.69
Stand-alone TP	40.0		42.8		42.8		54.5		41.4		42.8		39.3
Buffer capacity		4		4		4		3		3		4	
Starvation	0		0.036		0.021		0.0080		0.0029		0.067		0.083
Blockage	0.10		0.11		0.12		0.28		0.10		0.070		0
Work-in-process		1.52		0.50		2.83		2.41		0.52		0.054	

3 IU: Theoretical Foundations and Computational Tools (cont)

- **Computer simulation model:**
  - CSM is intended to represent a production system's *"digital twin"* (i.e., capturing **all** features of its behavior).
  - If such a model were created, performance metrics and efficacy of potential improvement projects could be evaluated by computer simulations (*with no need of analytical theory*).
  - Since CSM is intended to represent "everything" in system's behavior, *IU must measure "everything"*, if AU utilizes CSM.
  - Many believe that creating a "digital twin" is impossible and, moreover, unnecessary – since *"everything"* cannot be measured.
  - If this is true, "incomplete digital twin" or "incomplete measuring" could lead not only to quantitative errors , but to qualitative ones as well.

- Summary of the production system model properties:

	Part flow model (PFM)	Mathematical model (MM)	Computer simulation model (CSM)
Modeling	Easy	Difficult	Very difficult
Complexity of IU	Simple	Complex (requires real-time measurements of machine and buffer parameters involved in the block-diagram)	Very complex (requires real-time measurements of parameters of every element of the production system in the factory floor)
Utilization			
Existing systems	BN identification	Performance analysis & BN identification	Performance analysis & BN identification
Continuous improvement projects	Cannot be used	Efficacy analysis (using analytical techniques)	Efficacy analysis (using statistical tools)
Accuracy	Relatively high	Relatively high	High (if the digital twin is sufficiently precise)

- Based on the above, **SPS Advising Tool developed in this work uses IU to support MM employed by AU.**

4 AU: Theoretical Foundations and Computational Tools

- **Theoretical foundations of AU**: Theory of Production Systems Engineering
- **Computational tools of AU:** *PSE Toolbox*®
- Utilization of these tools in AU requires knowledge of methods developed in *PSE 2009* and subsequent publications.
- Therefore, these methods and computational tools (utilized in AU) are briefly outlined next.

- **Bottlenecks**:
  - Definition: BN is the machine with the largest effect on the system throughput:

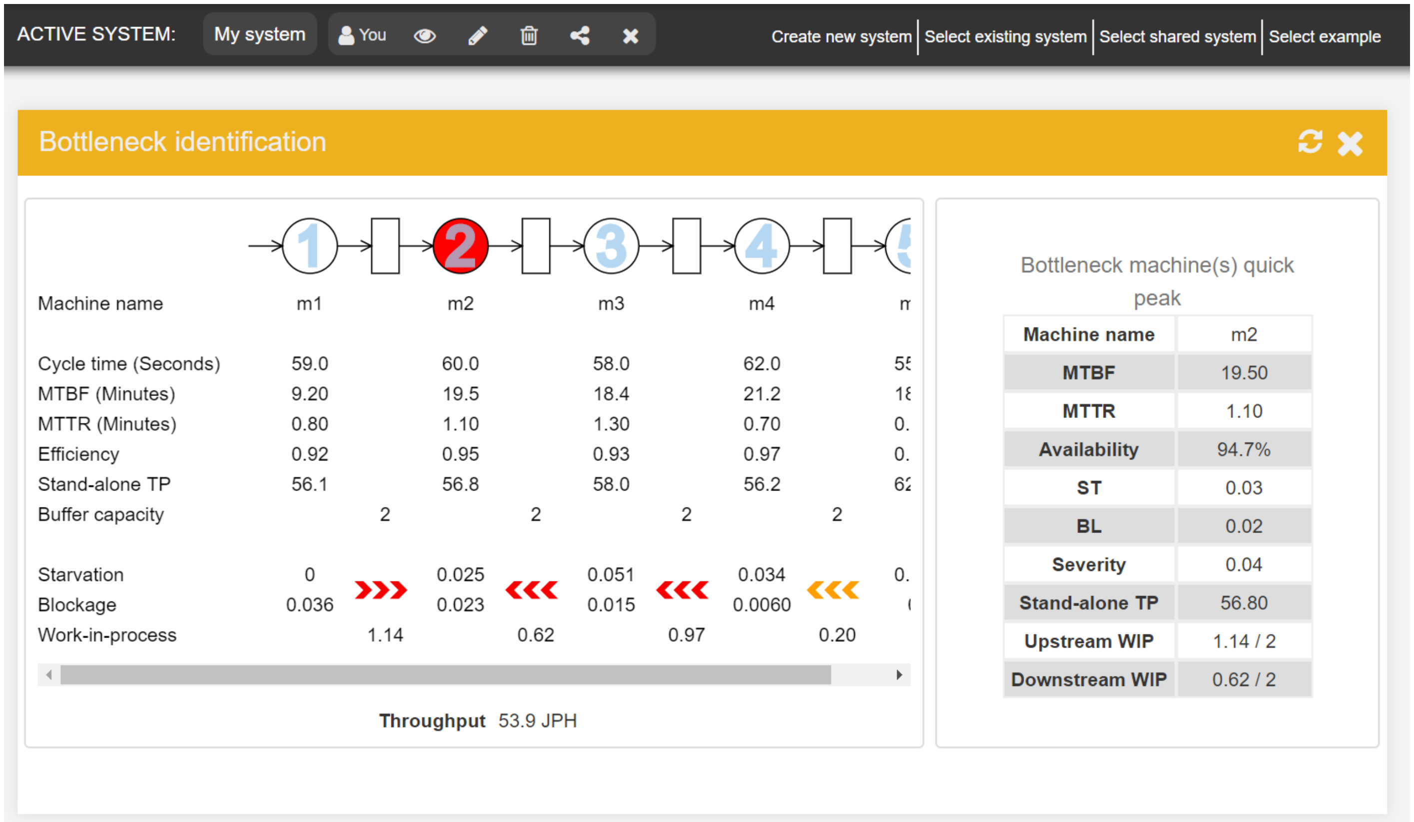
$$\frac{\partial TP}{\partial c_i} > \frac{\partial TP}{\partial c_j}, \forall j \neq i.$$

  - Since the derivatives involved cannot be evaluated analytically, the following approximation method has been developed:
    - Using *SPS Toolbox*, evaluate *BL* and *ST* of all machines.
    - Assign arrows between each two machines according to the rule: If $BL_i > ST_{i+1}$, assign arrow from m_i to m_{i+1}; if $BL_i < ST_{i+1}$, assign arrow from m_{i+1} to m_i. The machine with no emanating arrows in the BN (in the above sense).
    - If there are multiple machines with no emanating arrows, the one with the largest severity S_i is the primary BN:

$$\begin{aligned} S_1 &= |ST_2 - BL_1|, \\ S_i &= |ST_{i+1} - BL_i| + |ST_i - BL_{i-1}|, \quad i = 2, \cdots, M-1 \\ S_M &= |ST_M - BL_{M-1}|. \end{aligned}$$

4 AU: Theoretical Foundations and Computational Tools (cont)

- Bottlenecks (cont):
  - *PSE Toolbox* module “Bottleneck identification”:



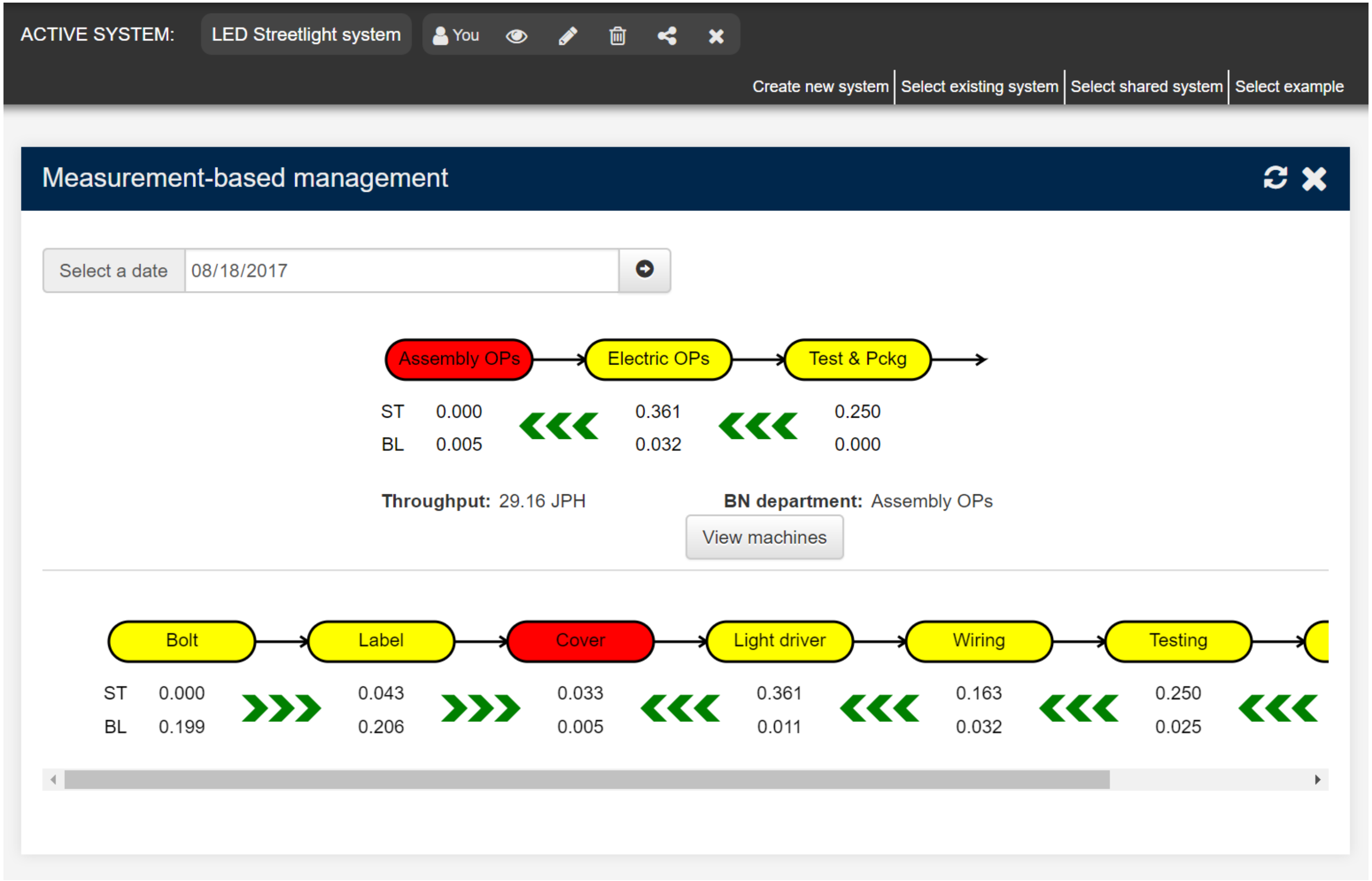
  - Note that BN is not the machine with the smallest stand-alone throughput.

4 AU: Theoretical Foundations and Computational Tools (cont)

- Buffering potency:
  - Definition: Buffering is:
    - *weakly potent* if BN is the machine with the smallest stand-alone throughput; otherwise, the buffering is *not potent*;
    - *potent* if it is weakly potent and, in addition, the stand-alone throughput of the BN machine is close to system's throughput, TP.
    - *strongly potent* if BN is potent and the system has the smallest buffering necessary to ensure this throughput.
- Measurement-based Management (MBM):
  - A method for production systems management based on measuring machines' *BL* and *ST*, identifying the BN, and, on this basis, making managerial decisions.

4 AU: Theoretical Foundations and Computational Tools (cont)

- *PSE Toolbox* module “Measurement-based Management”:



4 AU: Theoretical Foundations and Computational Tools (cont)

- **Leanness of buffering**:
  - To define lean buffering, the following parametrization is introduced:
    - *System efficiency*:

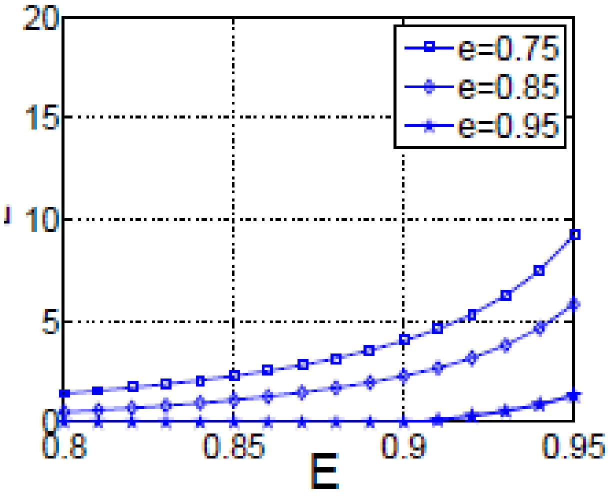
$$E = \frac{TP_N}{TP_\infty}$$

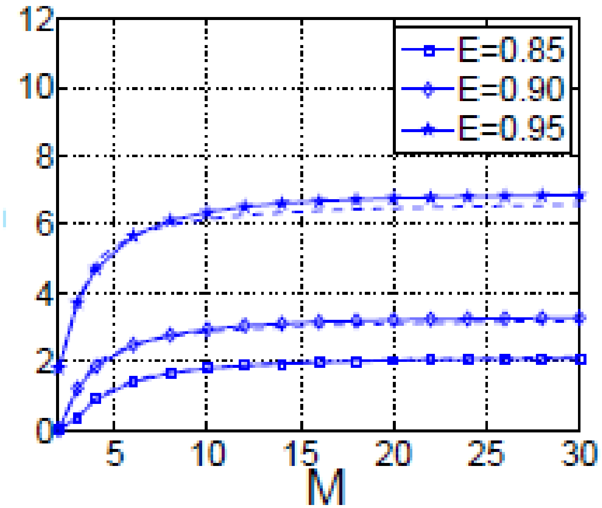
    - *Level of buffering*:

$$n = \frac{N}{T_{down}^{cycle}}, \quad \text{where} \quad T_{down}^{cycle} = \frac{T_{down}}{\tau}.$$

  - Definition: *Lean level of buffering* (n_E) is the smallest level of buffering necessary and sufficient to ensure the desired system efficiency, E.
  - *PSE 2009* provides methods and algorithms for n_E calculation for various types of system.
  - Given n_E, the lean buffer capacity is calculated as $N_E = T_{down}^{cycle} n_E$.

- Leanness (cont)
  - Lean buffers capacity a function of e, E, and M:



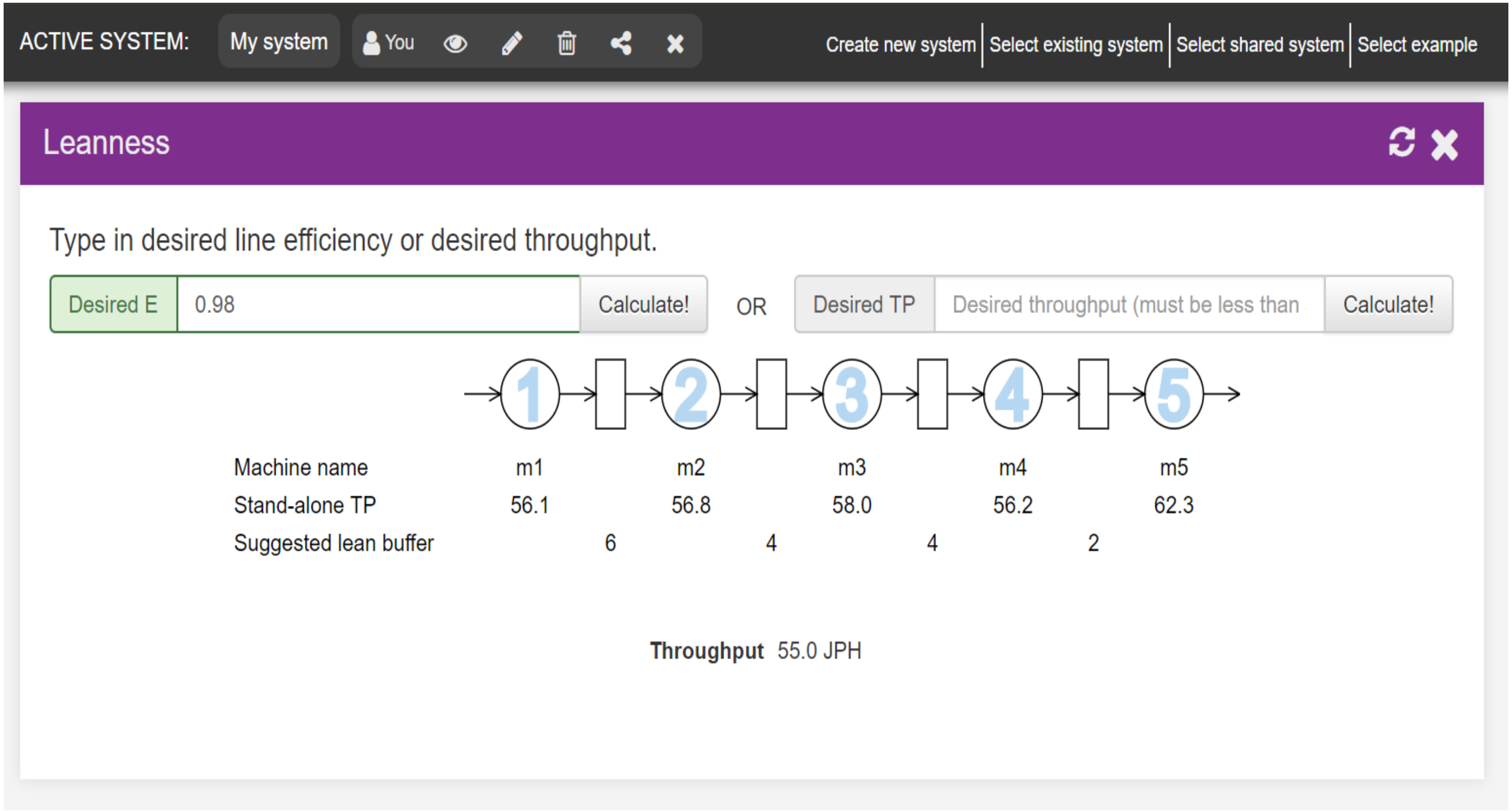


  - Rule-of-thumb for selecting lean buffering:

e	$E = 0.85$	$E = 0.90$	$E = 0.95$
0.85	3.4	5	9.8
0.90	2.7	3.9	7.2
0.95	1.6	2.4	4.3

4 AU: Theoretical Foundations and Computational Tools (cont)

- *PSE Toolbox* module “Leanness”:



4 AU: Theoretical Foundations and Computational Tools (cont)

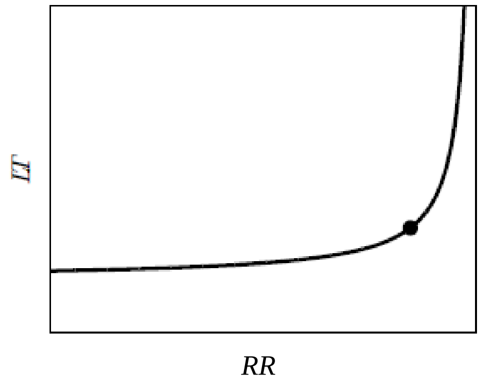
- Just-Right vs. Just-in-Time operation:
  - JIT is often understood as having no buffer between each pair of consecutive operations. This leads to low *WIP* and, unfortunately, low *TP* as well.
  - The opposite of JIT is having very large buffers. This leads to the largest *TP* but, unfortunately, to very large *WIP*.
  - The method of lean buffer design, discussed above, provides a compromise: It offers a possibility for calculating the smallest buffer capacity, which is necessary and sufficient to guarantee the desired throughput.
  - That is why we referred to it as *Just-Right* buffer capacity allocation.

4 AU: Theoretical Foundations and Computational Tools (cont)

- **Production lead time:**
  - Definition: *Production lead time* (*LT*) is the time a part spends in the system, being processed or waiting for processing.
  - *LT* is of particular importance in systems with large ("infinite") buffers, where it may be orders of magnitude larger than the total processing time.
  - Control of *LT* can be accomplished by throttling the raw material release rate (*RR*) so that desired lead time is obtained.
  - Since in systems with infinite buffers $TP = RR$, this implies that TP is also "throttled".
  - The relationship *LT* vs. *RR* or, equivalently, *LT* vs. *TP* is referred as *characteristic curve* (CC) of a production system.
  - Analytical expression for CC has been derived in a paper by S. Meerkov and C.-B. Yan (*M&Y* 2016), *IEEE Transactions on Automation Science and Engineering*, vol. 13, Issue 2, pp. 663-675, 2016.

4 AU: Theoretical Foundations and Computational Tools (cont)

- Production lead time (cont):
  - It has been shown that CC has a knee-type shape:



  - Having *RR* below the knee is undesirable because *TP* can be increased without a substantial increase of *LT*; operating above the knee is also undesirable, since *TP* is almost constant, but *LT* becomes large.
  - Thus, the desirable operating point is at the knee – the "*sweet point*".
  - In *M&Y 2016*, the position of the sweet point is quantified as the CC point with the largest curvature.

- Production lead time (cont):
  - Also, *M&Y 2016* provides analytical expressions for *RR*, which ensures operation at the sweet point (or at any other desired point of CC). These expressions depend on the machine parameters.
  - If machine parameters are not known precisely, *M&Y 2016* provides a feedback control law for raw material release specified by

$$E(s+1) = \begin{cases} \hat{E}^*_{RI}, & \text{if } WIP_{total}(s) \leqslant \widehat{WIP}_{nominal} \\ 0, & \text{otherwise,} \end{cases}$$

where

$$\hat{E}^*_{RI} = \left\lfloor \frac{RI}{\tau} \hat{e}^*_0(lt_d) \right\rfloor \qquad \widehat{WIP}_{nominal} = \frac{\hat{e}^*_0}{\tau}(LT_d - M\tau).$$

  - It has been shown that this closed-loop control ensures *LT* close to the desired, even when the open-loop control leads to infinite *LT* (due to variations of the machine parameters).

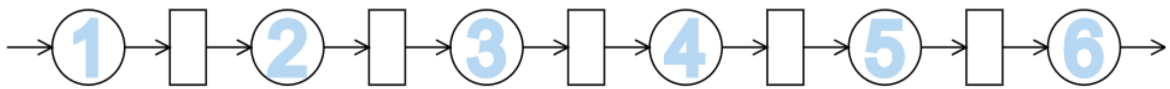
4 AU: Theoretical Foundations and Computational Tools (cont)

- *PSE Toolbox* module “Lead time analysis and control”:
  - *LT* analysis:

Lead time analysis

Lead time unit for analysis: ○ Seconds ◉ Minutes ○ Hours

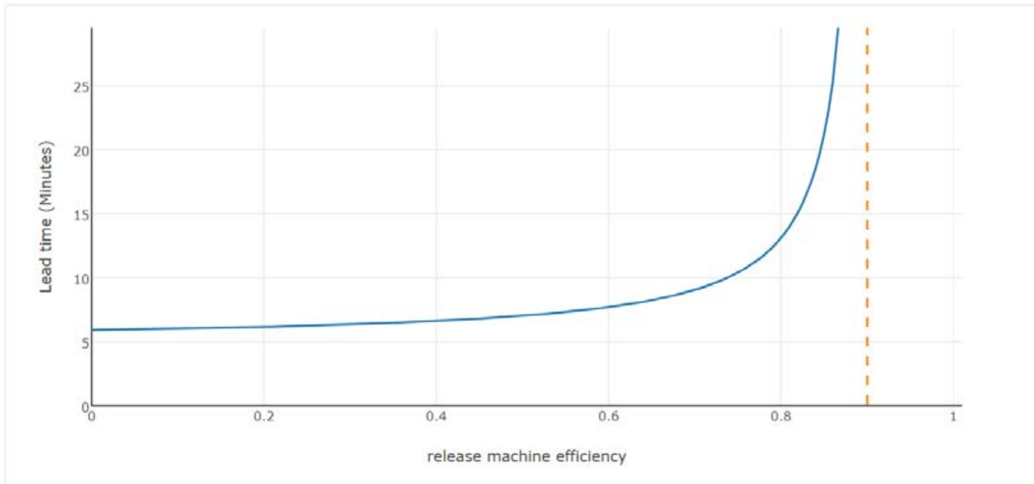
Cycle time: 1.00 Minute



Machine name	Release machine	m1	m2	m3	m4	m5
MTBF	--	9.00	9.00	9.00	9.00	9.00
MTTR	--	1.00	1.00	1.00	1.00	1.00
Efficiency	--	0.90	0.90	0.90	0.90	0.90

Lead time > 5.90 (Minutes)

- *PSE Toolbox* module “Lead time analysis and control”:
  - *LT* control:



LTd 10 Minutes

RI 60 Minutes

Calculate

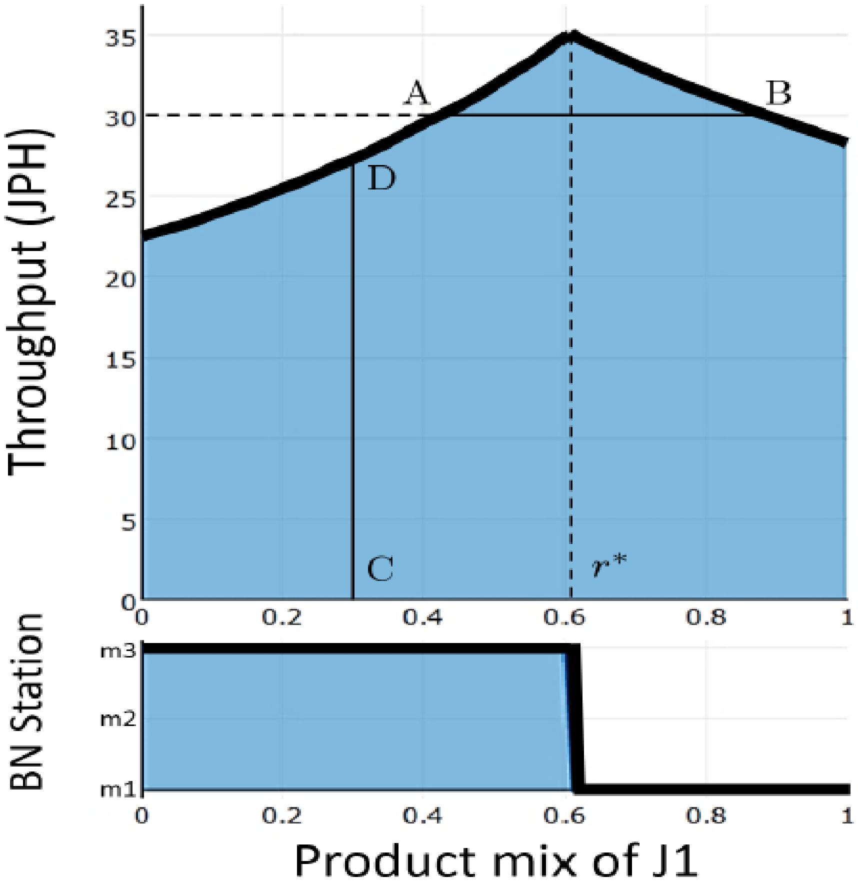
Lead-time control	
Per-cycle release rate	0.7380
Per-RI release rate	44 parts / 60 Minutes
WIP in release buffer	1.19
WIP	1.19, 1.19, 1.19, 1.19
Total WIP	5.97
Closed-loop WIP threshold	4
Optimal CONWIP	4

4 AU: Theoretical Foundations and Computational Tools (cont)

- **Multi-job production systems**:
  - Definition: MJP is a class of flexible production systems intended to produce several job-types using the same sequence on manufacturing operations.
  - MJP systems are defined not only by the machine and buffer parameters, but also by the desired product-mix, $\boldsymbol{r} = [r_1, \ldots r_S], \sum_{i=1}^{S} r_i = 1$ (which may be changing on a daily basis).
  - All characteristics of MJP systems performance (e.g., TP, BN, WIP) depend on $\boldsymbol{r}$.
  - A theory of MJP systems has been developed in P. Alavian, P. Denno, and S.M. Meerkov (*A&D&M 2017*), accepted for publication in *IJPR* (http://www.tandfonline.com/doi/pdf/10.1080/00207543.2017.1338779?needAccess=true)
  - A major part of this theory is Product-mix Performance Portrait (PMPP), which represents MJP systems BN and TP as functions of $\boldsymbol{r}$.

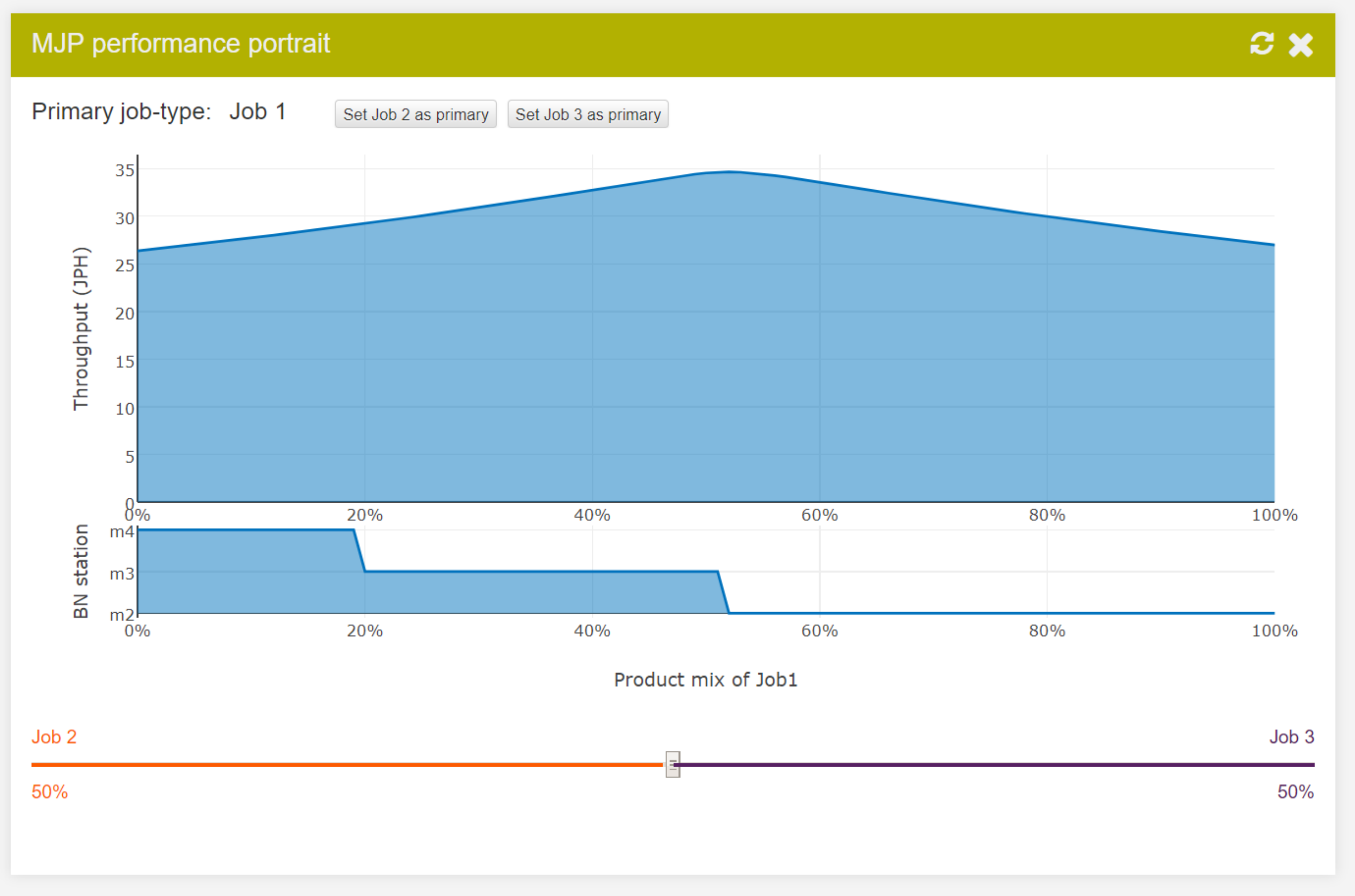
4 AU: Theoretical Foundations and Computational Tools (cont)

- Multi-job production systems (cont):
  - PMPP for $S = 2$:



4 AU: Theoretical Foundations and Computational Tools (cont)

- *PSE Toolbox* module "MJP performance portrait":



5 OU: THEORETICAL FOUNDATIONS AND COMPUTATIONAL TOOLS

- **Theoretical foundation of OU:**
  - Based on optimization techniques in the space of production system parameters.
  - More precisely, given a desired system improvement and the current status of the system at hand (provided by AU), OU is supposed to find the most efficient way of modifying the machine and buffers parameters so as to transfer the system from its current to the desired state.
  - This is accomplished using the *PSE Toolbox* to quantify the utility of various points in the parameter space and various search techniques.
- **Computational tools of OU:**
  - OU uses all modules of *PSE Toolbox* to find optimal continuous improvement project.

6 SPS AT: ARCHITECTURE, DESIGN, OPERATION, AND VERIFICATION

- ***SPS Advising Tool*® architecture** (home page):

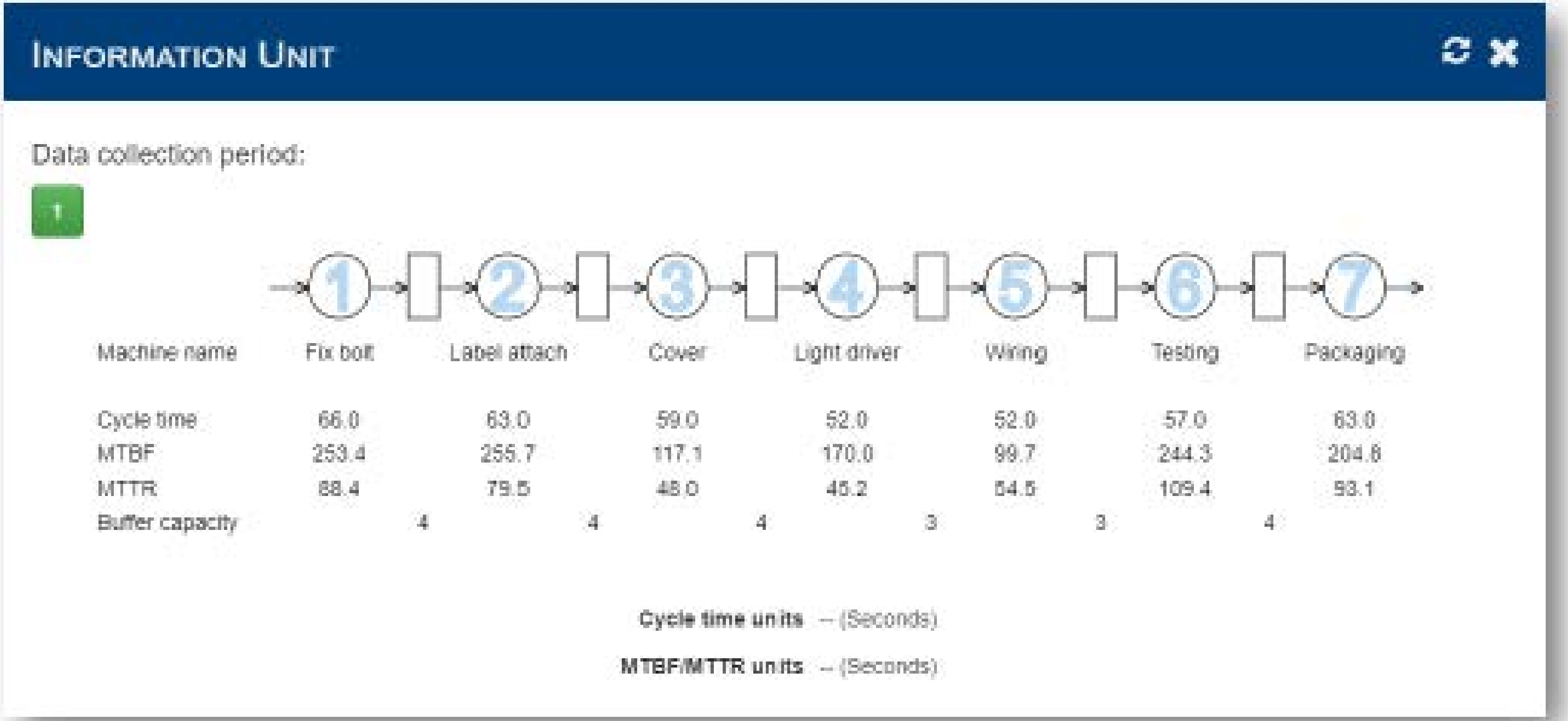
6 SPS AT: ARCHITECTURE, DESIGN, OPERATION, AND VERIFICATION (CONT)

- ***SPS Advising Tool*® design**:
  - Develop (off-line) and upload into the “System” block a MM of the production at hand
  - “Connect” IU with the sensors monitoring the performance of the machines and buffers involved into MM
  - “Connect” AU with the *PSE Toolbox*® modules necessary for performance analysis of the system at hand
  - Develop and upload into OU search algorithms necessary for developing optimal improvement advice.
  - Develop and upload into the “Measured productivity improvement” block algorithms for the required calculations
  - Train factory floor personnel in carrying out required managerial functions.

6 SPS AT: Architecture, Design, Operation, and Verification (cont)

- ***SPS Advising Tool*® operation:**
  - Selecting “System” block:

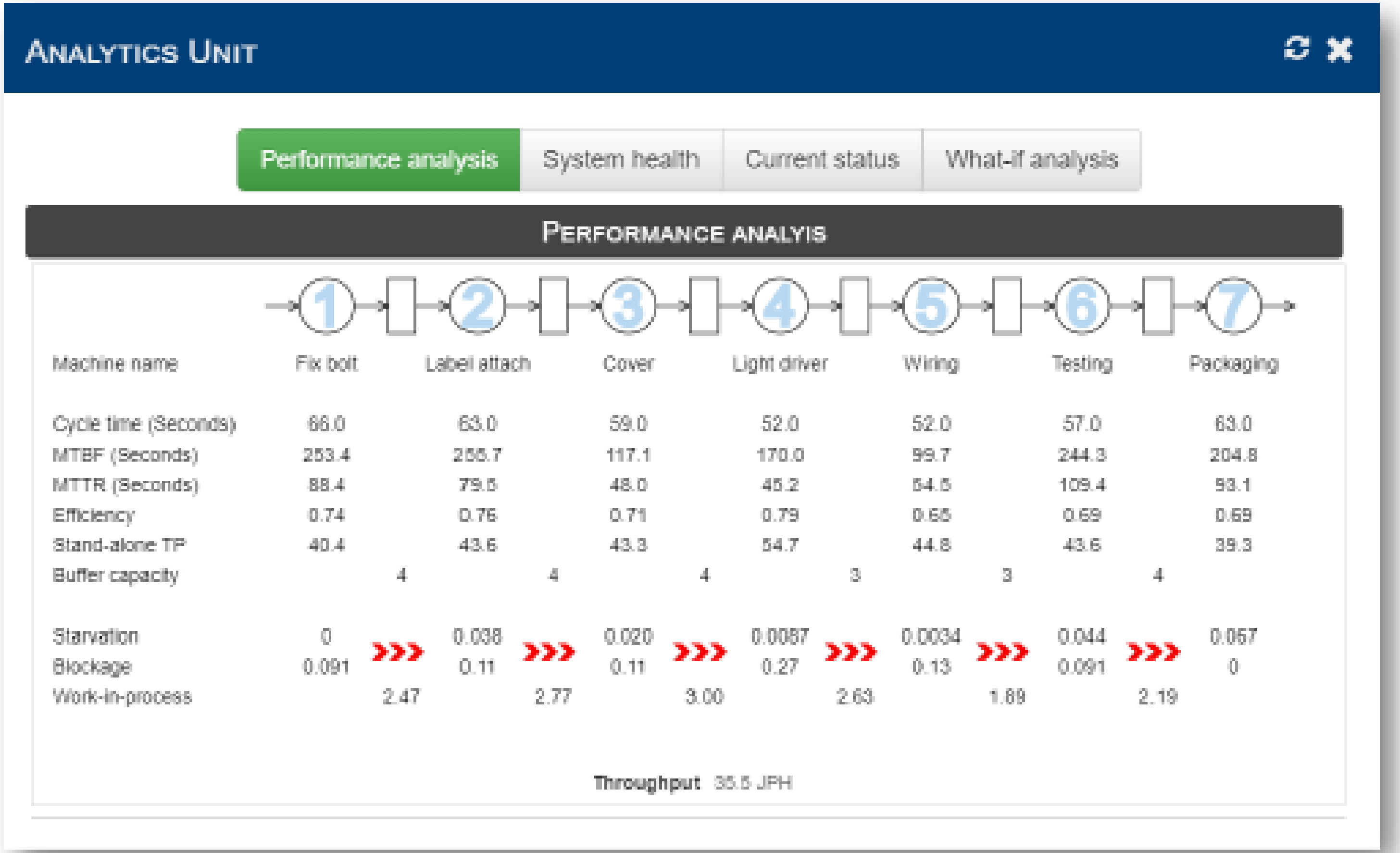
- *SPS Advising Tool*® operation (cont):
  - Selecting "Information Unit":



Machine name	Fix bolt		Label attach		Cover		Light driver		Wiring		Testing		Packaging
Cycle time	66.0		63.0		59.0		52.0		52.0		57.0		63.0
MTBF	253.4		255.7		117.1		170.0		99.7		244.3		204.8
MTTR	88.4		79.5		48.0		45.2		54.5		109.4		93.1
Buffer capacity		4		4		4		3		3		4	

6 SPS AT: Architecture, Design, Operation, and Verification (cont)

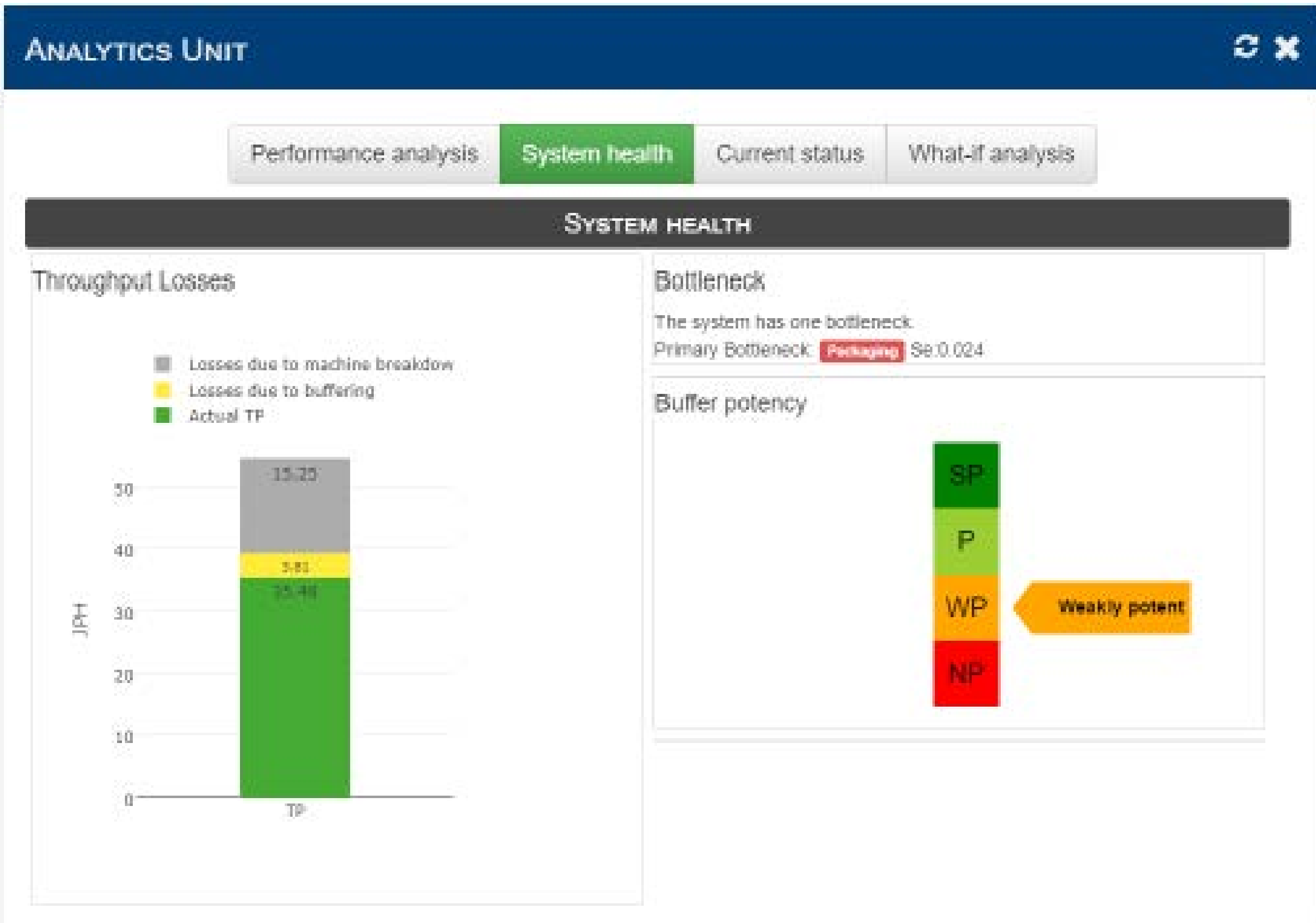
- *SPS Advising Tool*® operation (cont):
  - Selecting "Analytics Unit":



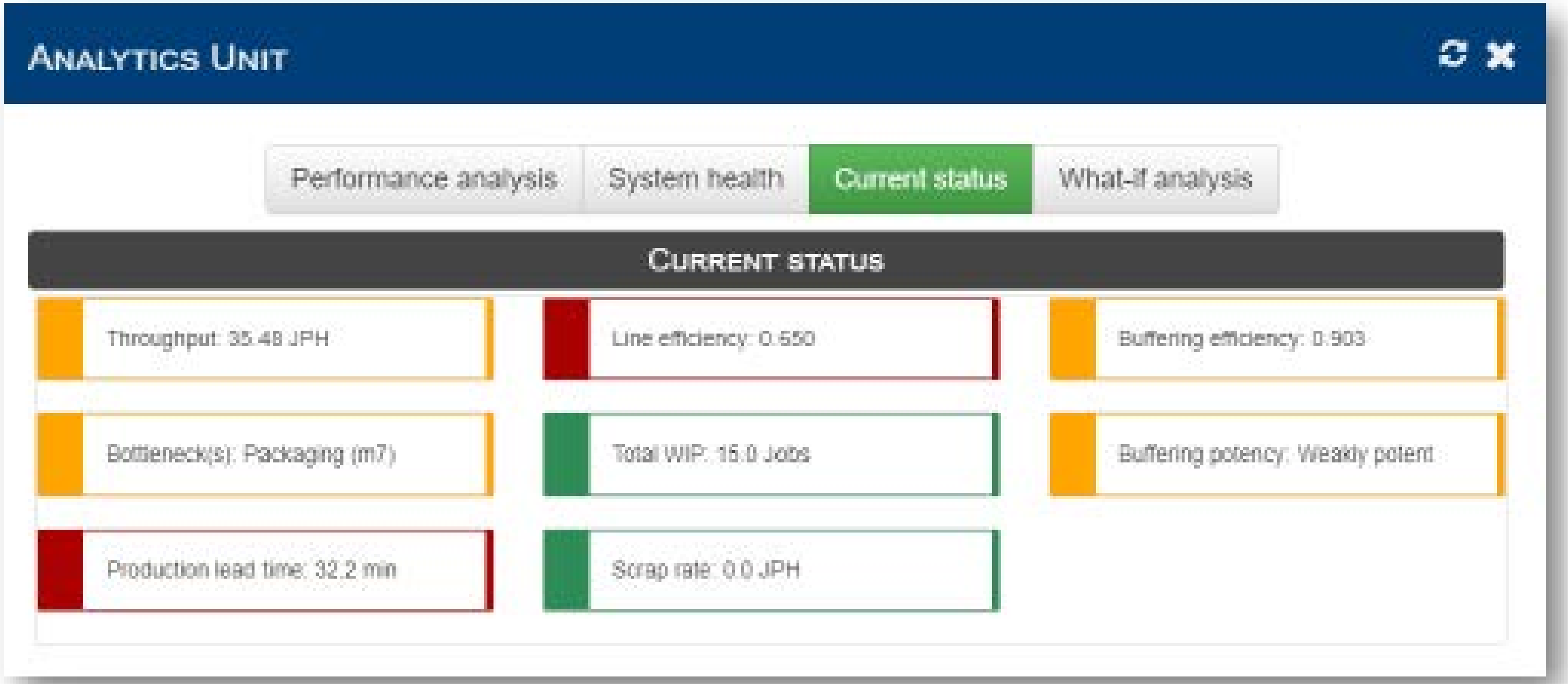
Machine name	Fix bolt		Label attach		Cover		Light driver		Wiring		Testing		Packaging
Cycle time (Seconds)	66.0		63.0		59.0		52.0		52.0		57.0		63.0
MTBF (Seconds)	253.4		255.7		117.1		170.0		99.7		244.3		204.8
MTTR (Seconds)	88.4		79.5		48.0		45.2		54.5		109.4		53.1
Efficiency	0.74		0.76		0.71		0.79		0.65		0.69		0.69
Stand-alone TP	40.4		43.6		43.3		54.7		44.8		43.6		39.3
Buffer capacity		4		4		4		3		3		4	
Starvation	0		0.038		0.020		0.0087		0.0034		0.044		0.057
Blockage	0.091		0.11		0.11		0.27		0.13		0.091		0
Work-in-process		2.47		2.77		3.00		2.63		1.89		2.19	

Throughput 35.5 JPH

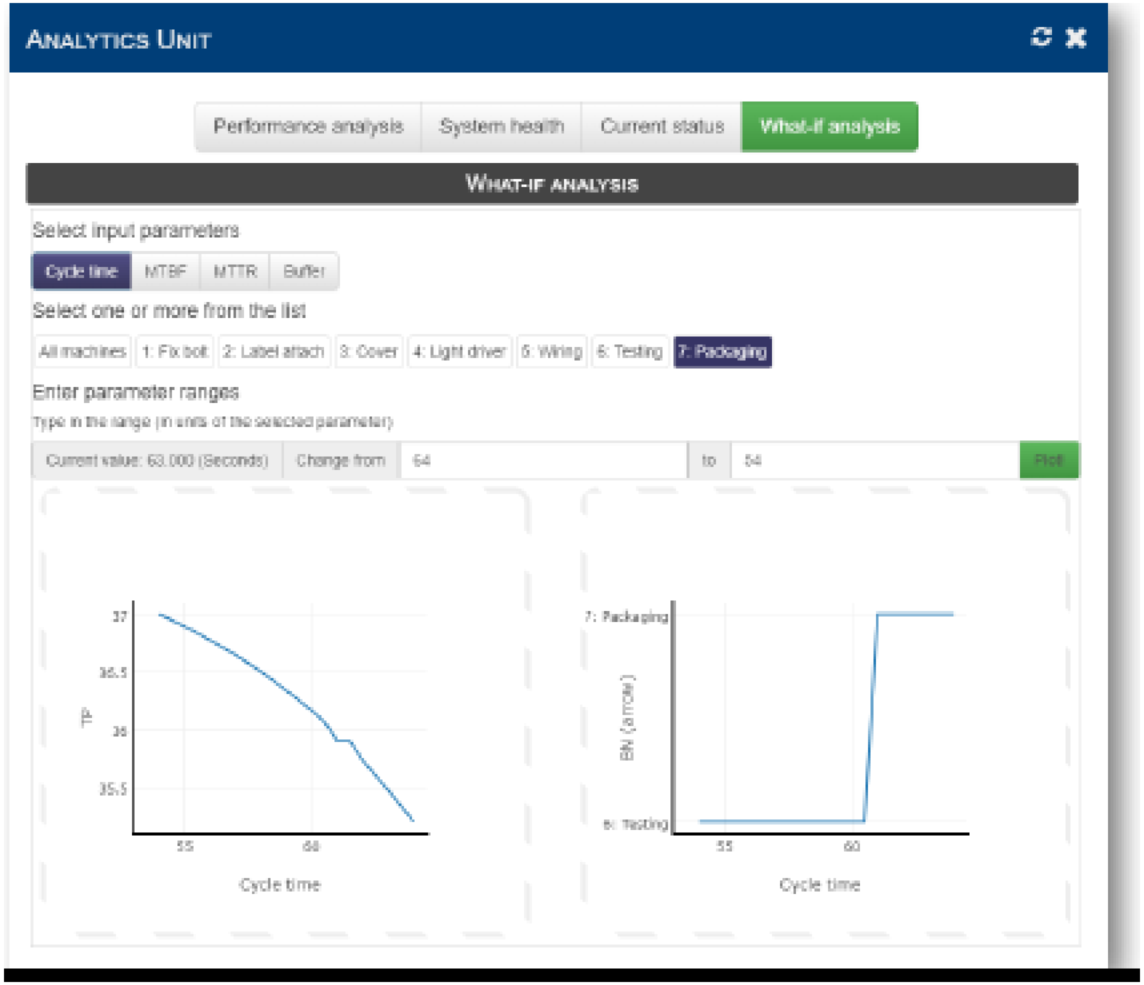
- *SPS Advising Tool®* operation (cont):
  - Selecting “Analytics Unit” (cont):



- *SPS Advising Tool*® operation (cont):
  - Selecting “Analytics Unit” (cont):

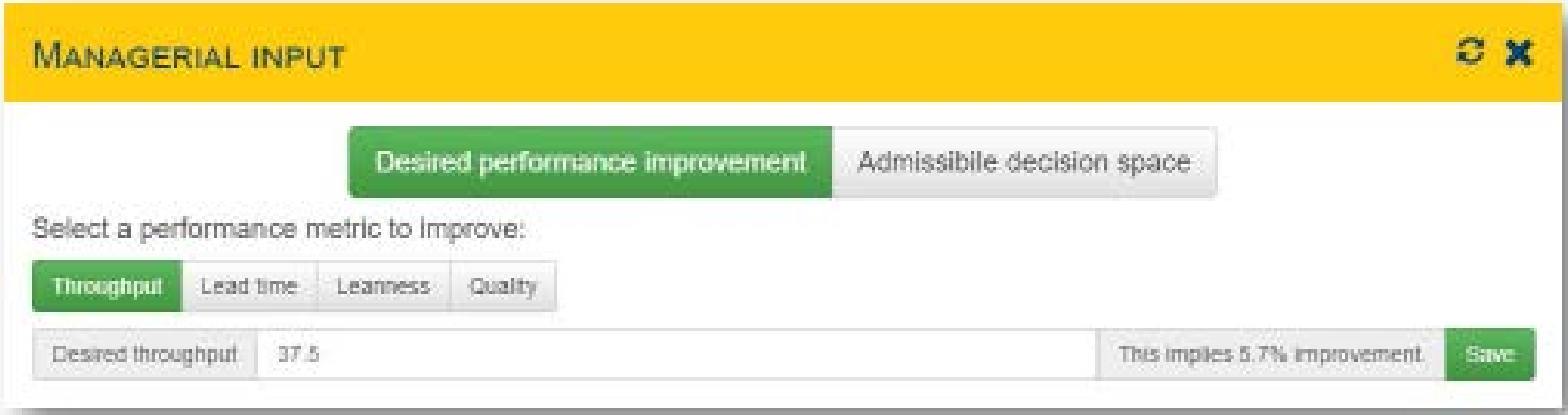


- *SPS Advising Tool*® operation (cont):
  - Selecting "Analytics Unit" (cont):



6 SPS AT: Architecture, Design, Operation, and Verification (cont)

- *SPS Advising Tool*® operation (cont):
  - Selecting “Managerial input” block:



6 SPS AT: Architecture, Design, Operation, and Verification (cont)

- *SPS Advising Tool*® operation (cont):
  - Selecting “Managerial input” block (cont):

MANAGERIAL INPUT

Desired performance improvement | Admissibile decision space

Line	Machine	Name	Current cycle time of Job 1	Min cycle time of Job1	Current MTTR	Min MTTR
Main	1	Fix bolt	66.0	59	86.3	80.0
Main	2	Label attach	63.0	56	79.5	72.0
Main	3	Cover	59.0	53	48.0	43.0
Main	4	Light driver	52.0	46	45.2	40.0
Main	5	Wiring	52.0	46	54.4	49.0
Main	6	Testing	57.0	51	109.4	98.0
Main	7	Packaging	63.0	56	93.1	84.0

Save

- *SPS Advising Tool*® operation (cont):
  - Selecting "Optimization unit":

Optimization Unit: Advice to the Manager

The goal of reaching TP of 37.50 JPH can be satisfied.

Testing (Machine: 6)

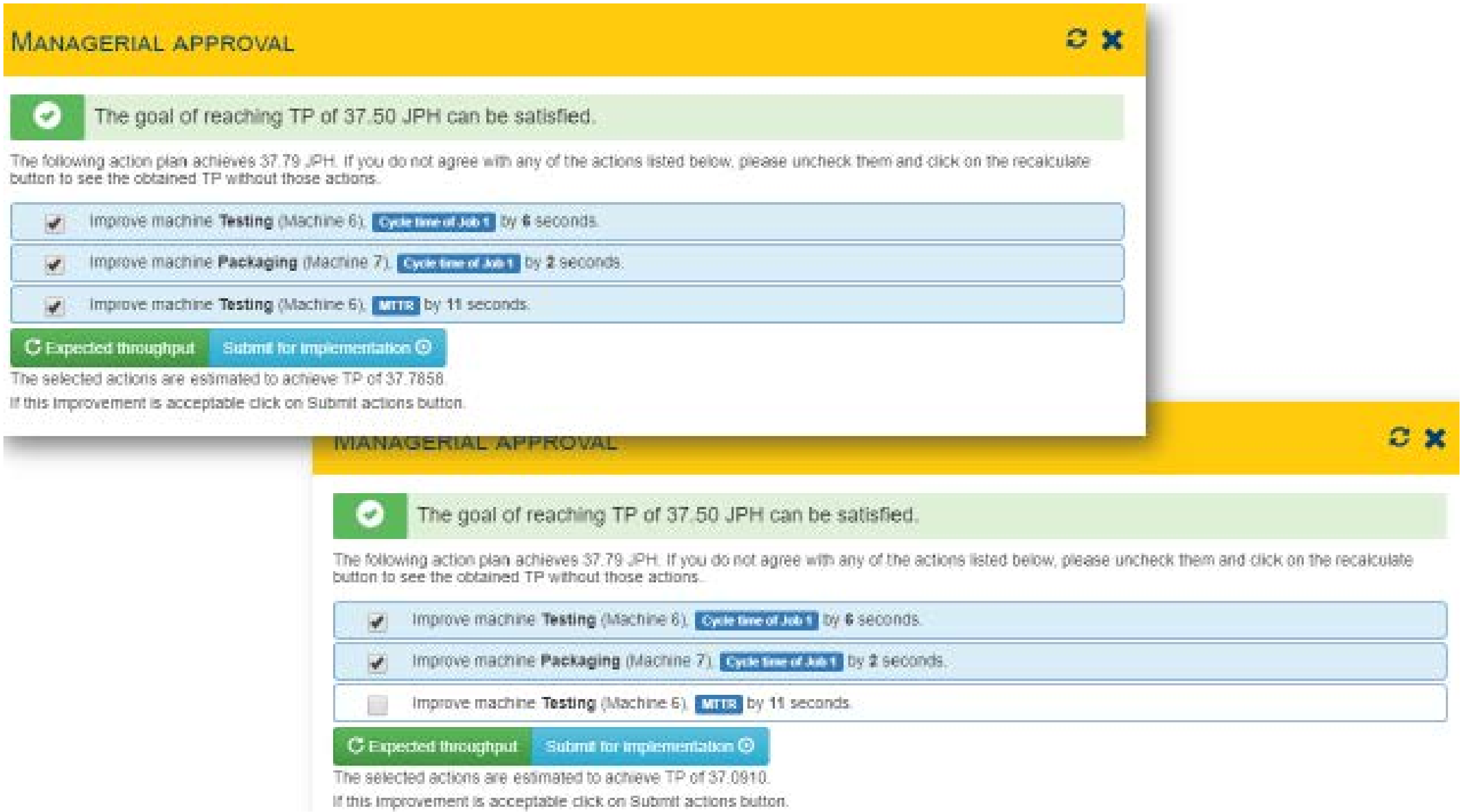
Parameter	Current value	Improvement	New value
Cycle time	57	6	51
MTTR	109.3733	11	98.3733

Packaging (Machine: 7)

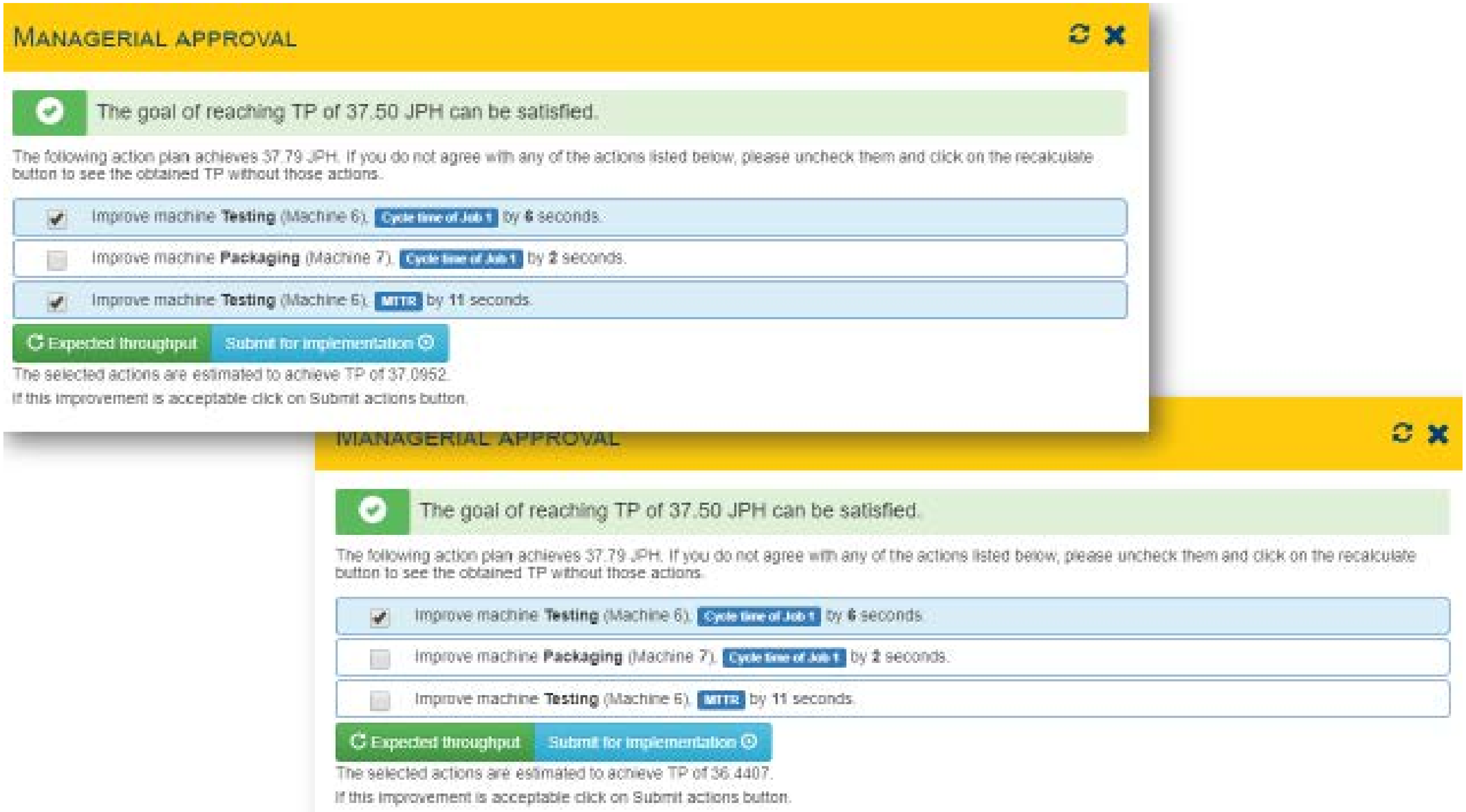
Parameter	Current value	Improvement	New value
Cycle time	63	2	61

6 SPS AT: Architecture, Design, Operation, and Verification (cont)

- *SPS Advising Tool*® operation (cont):
  - Selecting “Managerial approval” block:



- *SPS Advising Tool*® operation (cont):
  - Selecting “Managerial approval” block (cont):



6 SPS AT: ARCHITECTURE, DESIGN, OPERATION, AND VERIFICATION (CONT)

- *SPS Advising Tool*® verification:
  - Experimental verification procedure:
    - Design a discrete-event simulation model (DESM) of the system at hand
    - Run DESM with machine parameters approved by the Operations Manager
    - Statistically evaluate the resulting performance metrics
    - Compare the results obtained with those predicted by OU.
  - Results obtained (selecting the "Measured productivity improvement" block)

MEASURED PRODUCTIVITY IMPROVEMENT

Comparison of TP between periods 1 and 2

	Period 1		Period 2
Estimated TP	35.48JPH	Expected improvement: 6.5%	37.79JPH
Actual TP	33.26JPH	Obtained improvement: 5.9%	35.23JPH

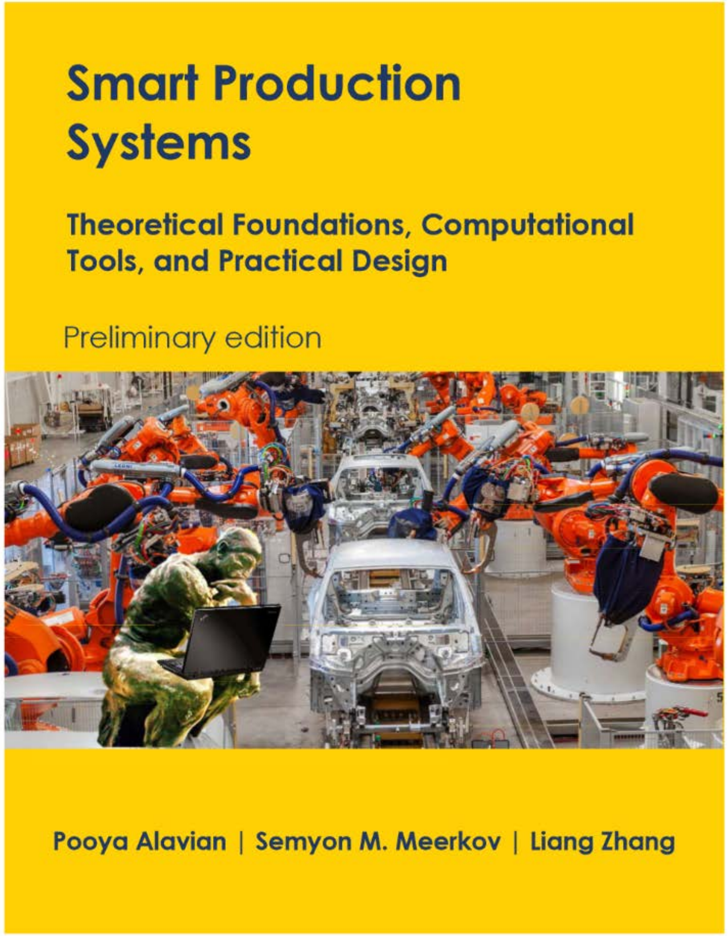
7 CONCLUDING REMARKS

- **SPS potential impact: theoretical**
  - The SPS potential theoretical impact is due its effect on Control Theory. While this theory contributed substantially to automation of machine tools and material handling devices, it had almost no effect on decision-making in manufacturing environment. Analysis and design of Smart Production Systems may lead to a new page in Control Theory – automation of decision-making.

- **SPS potential impact: practical**
  - The SPS potential practical impact is on the productivity improvement. In dozens of continuous improvement projects carried out in the last 30 years, we observed that throughput losses of 10%-20% are quite common in practice. This implies that reducing these losses, for instance, in half (which SPS brings in the realm of possibility), would result in 5%-10% of productivity improvement. That is why we believe that development and deployment of SPSs is of singular practical importance.

7 CONCLUDING REMARKS (CONT)

- The results included in this talk are described in more details in the forthcoming book:



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