

Supplementary Information

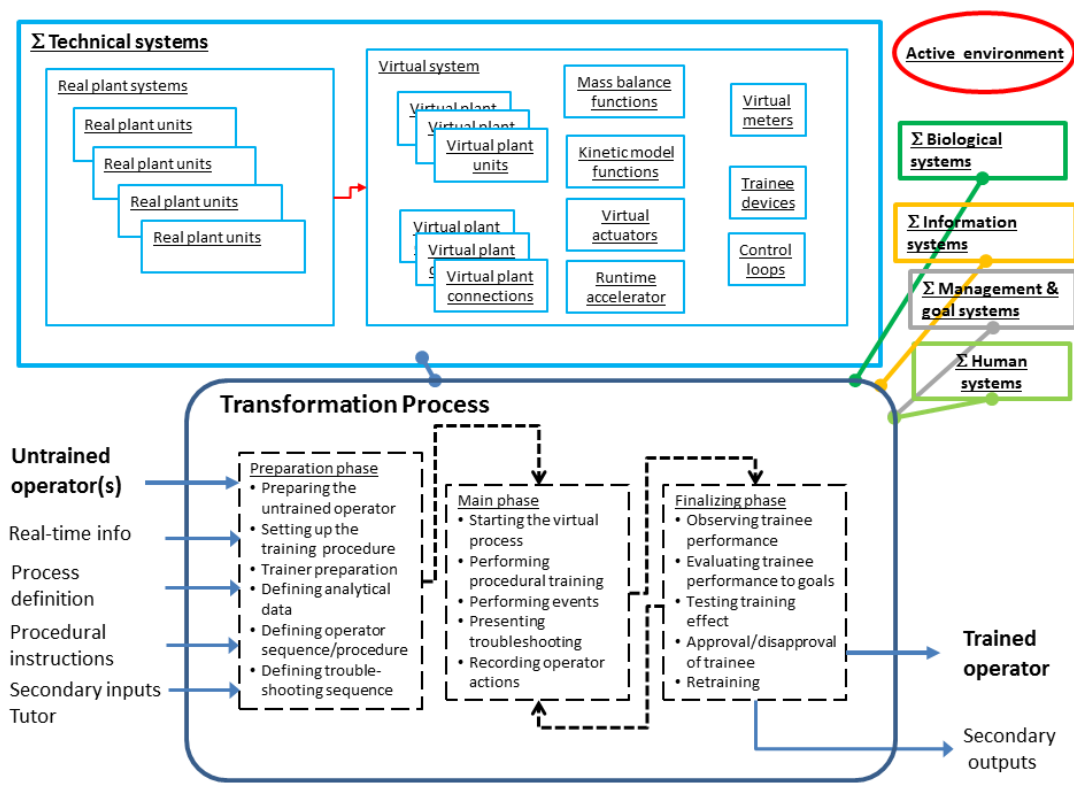


Figure S1. Zoom-in Hubka-Eder map of the technical systems.

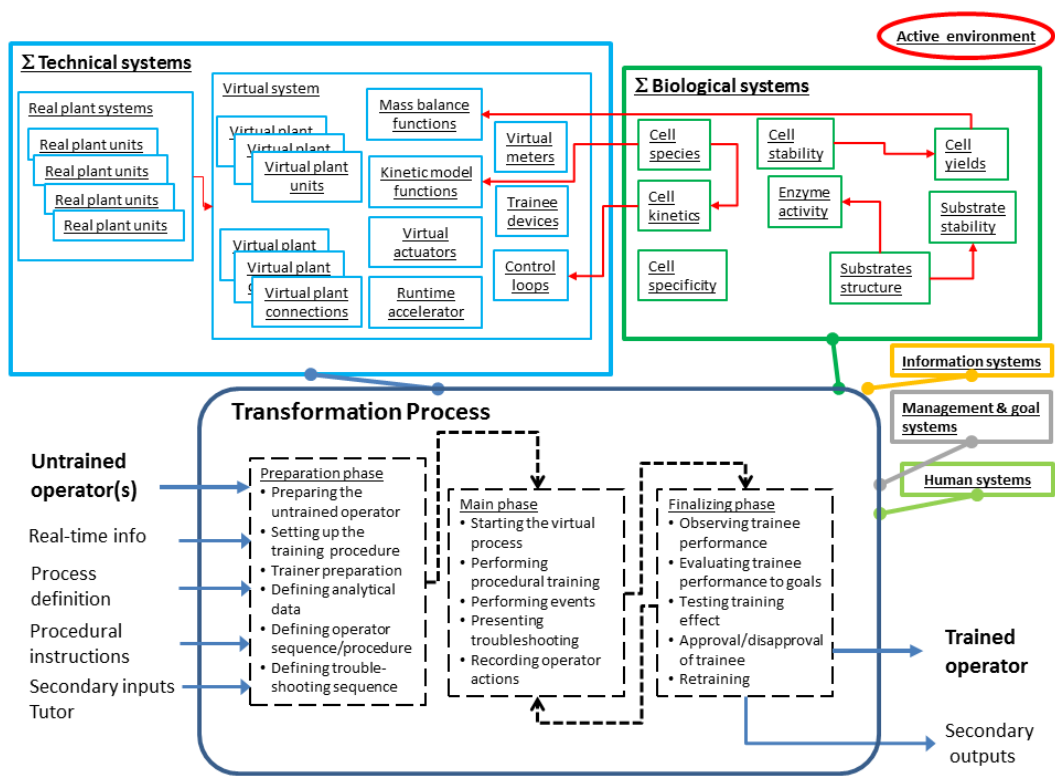


Figure S2. Zoom-in H-E map of the biological systems.

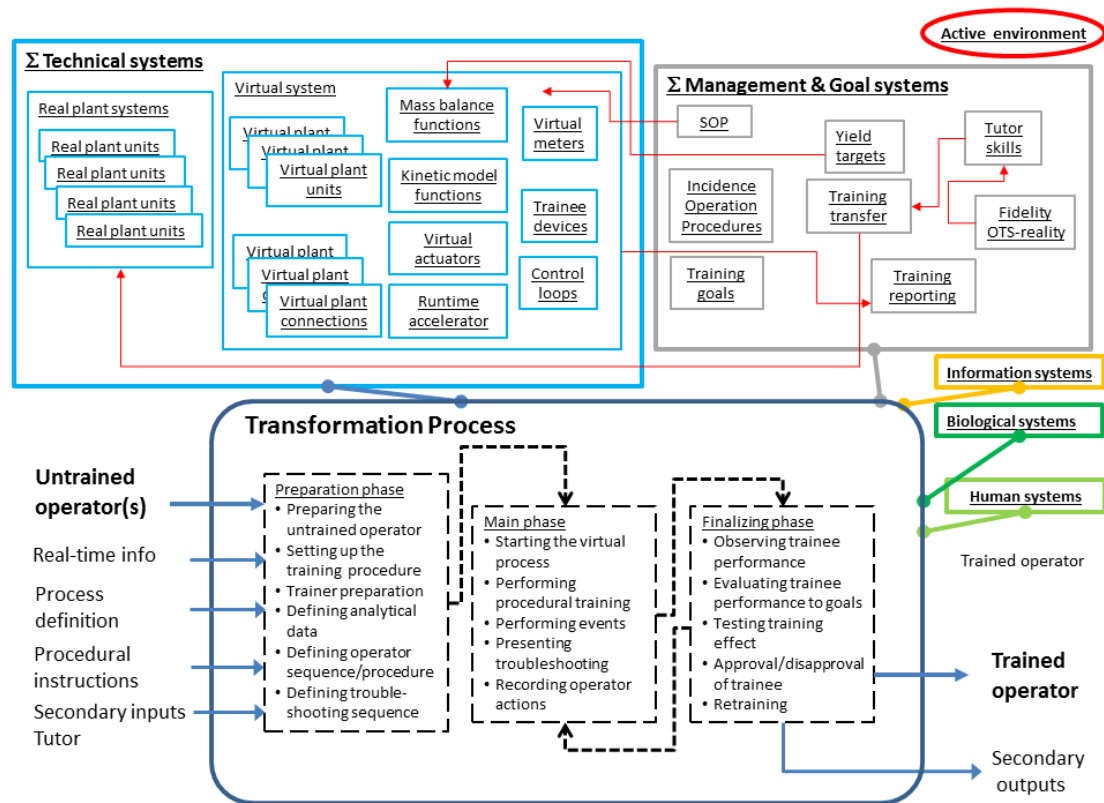
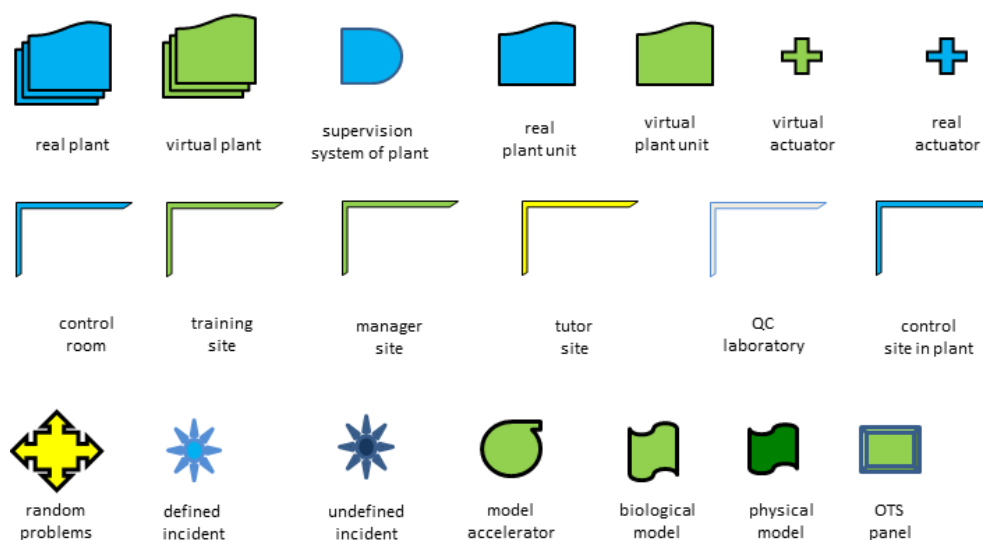


Figure S3. Zoom-in H-E map of the management and goal systems.

Technical systems



Biological systems



(a)

Figure S4. Cont.

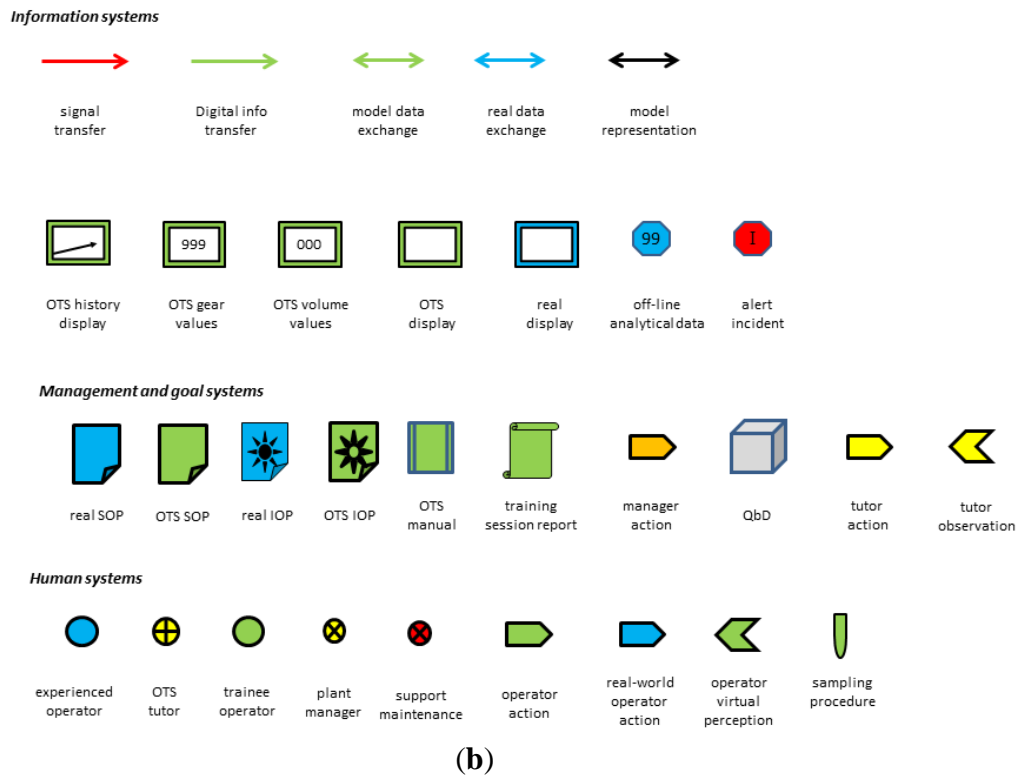
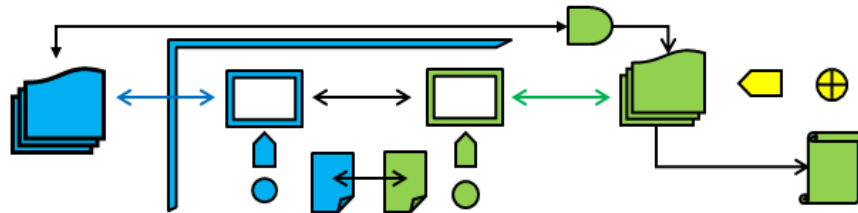
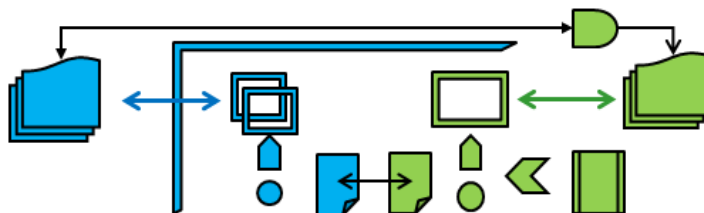
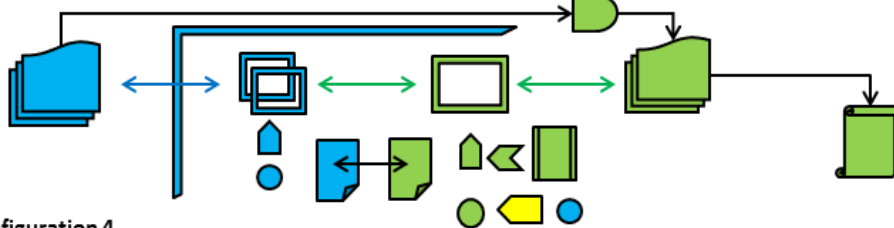
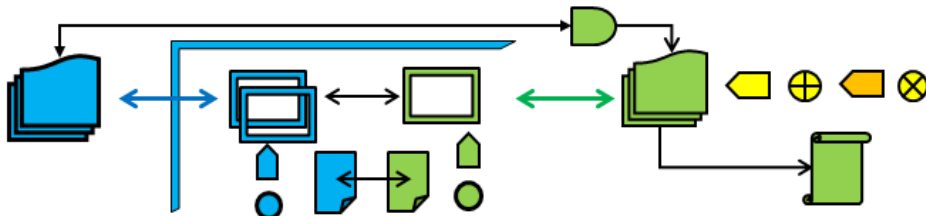
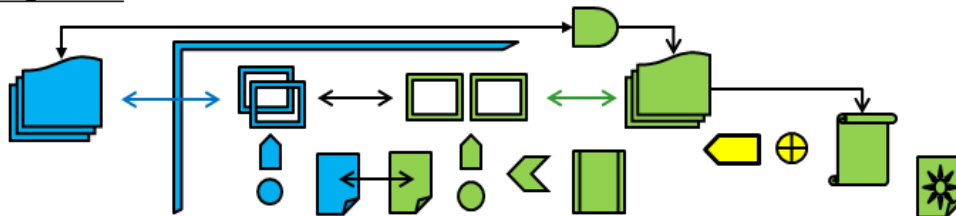
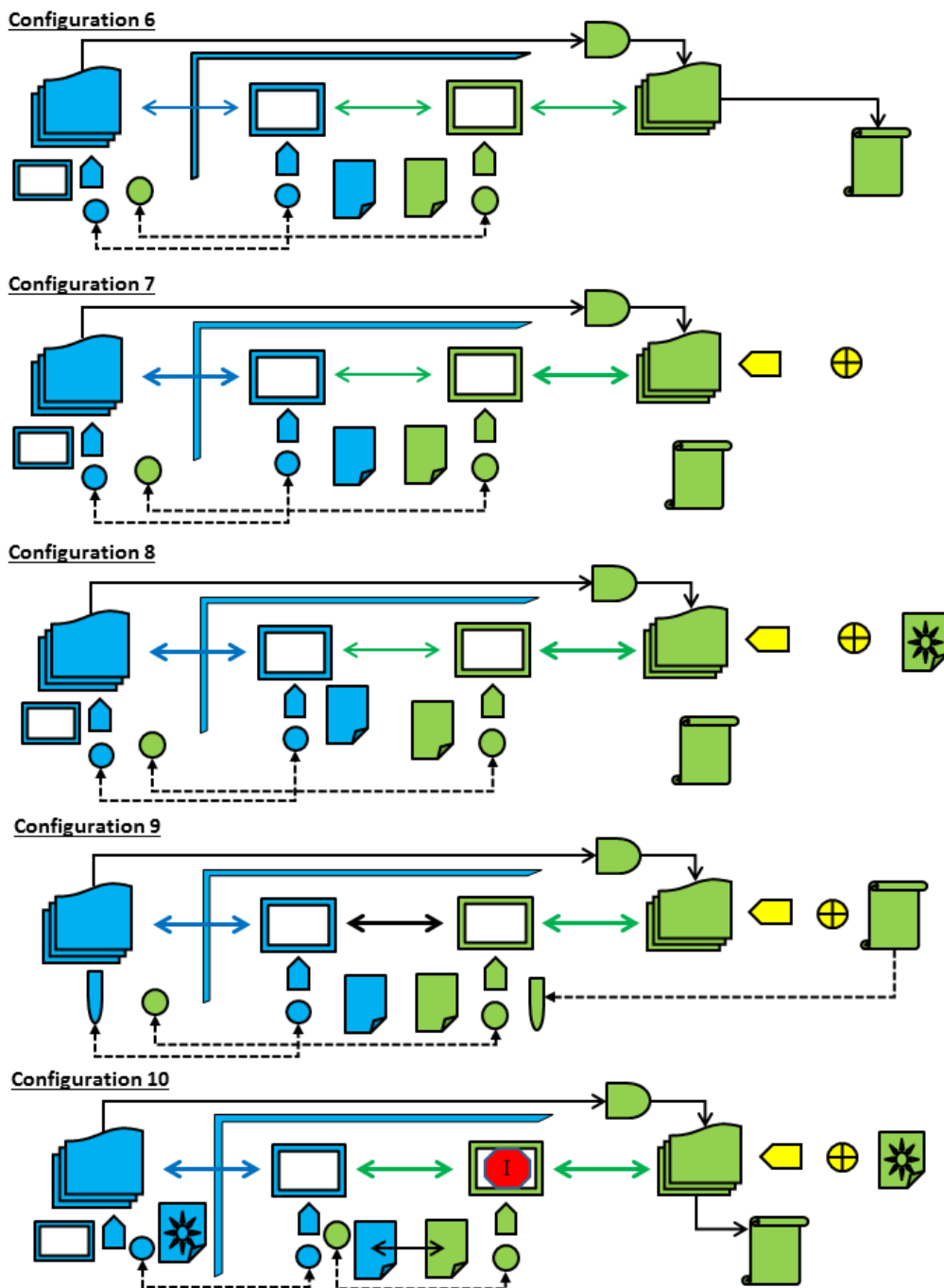
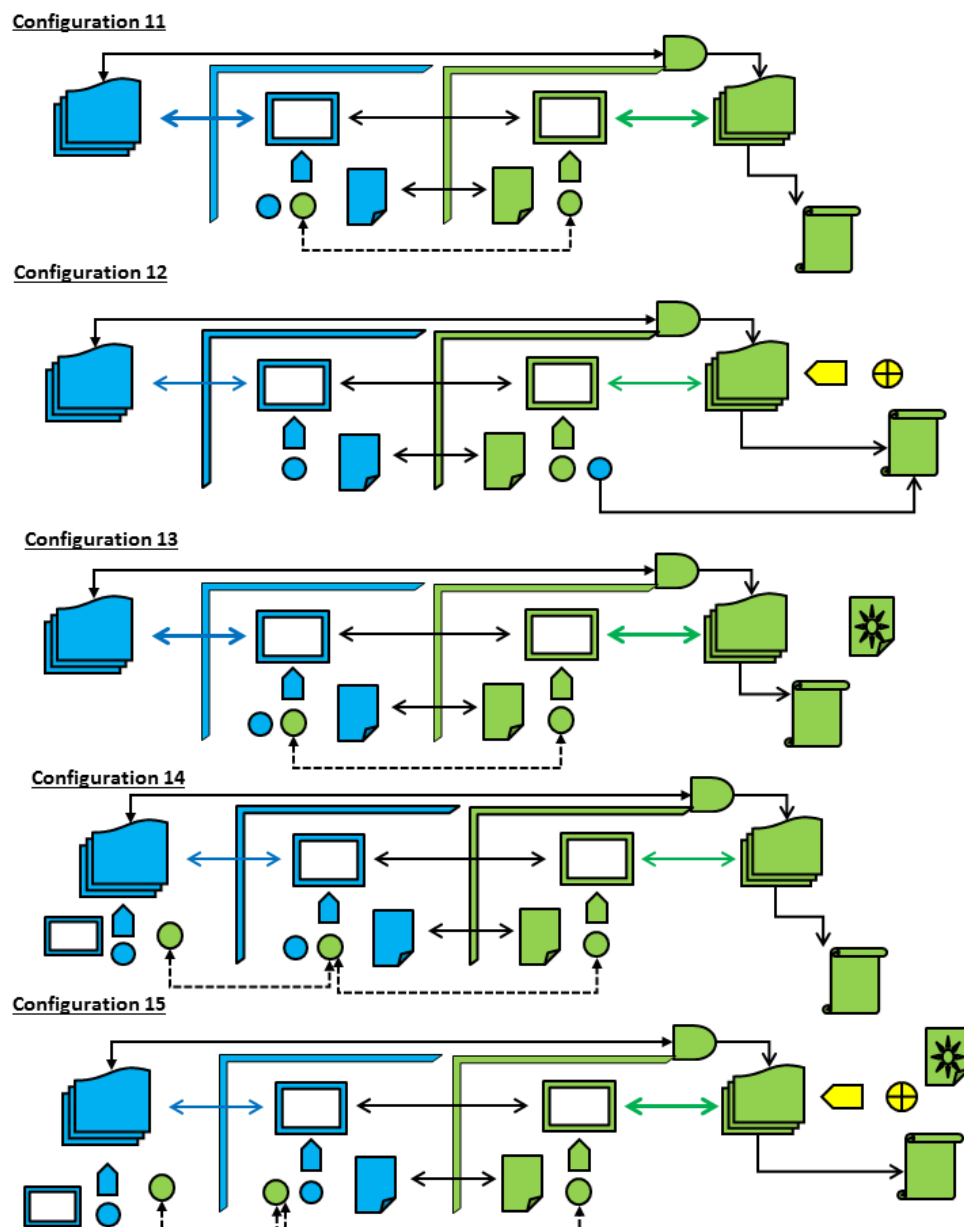


Figure S4. Functional permutation elements (complete collection). Not all of the elements are used in the permutation examples shown in Fig. S5 below. (a) Elements in the technical and biological systems; (b) Elements from the information, management and goal and human systems.

Category I (off-plant)Configuration 1Configuration 2Configuration 3Configuration 4Configuration 5Figure S5. *Cont.*

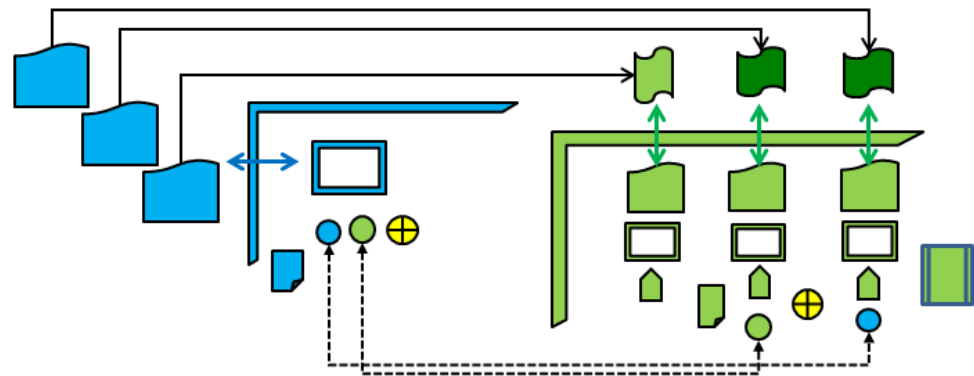
Category II (in-plant)



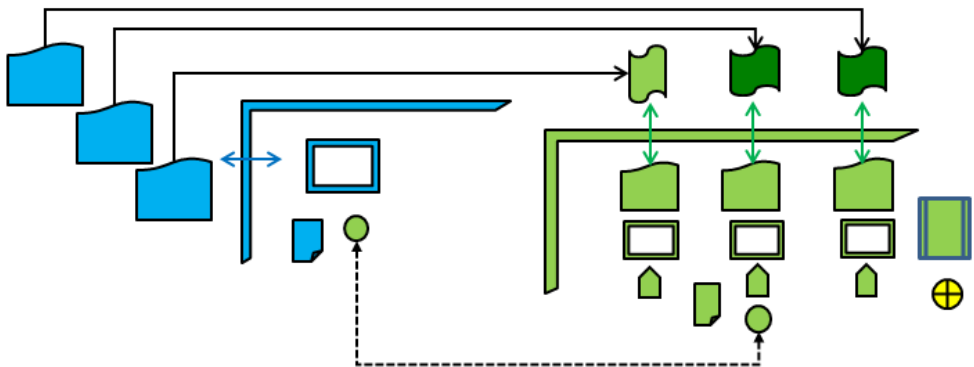
Category III (off-control room)**Figure S5.** *Cont.*

Category IV (distributed simulator set-ups)

Configuration 16



Configuration 17



Configuration 18

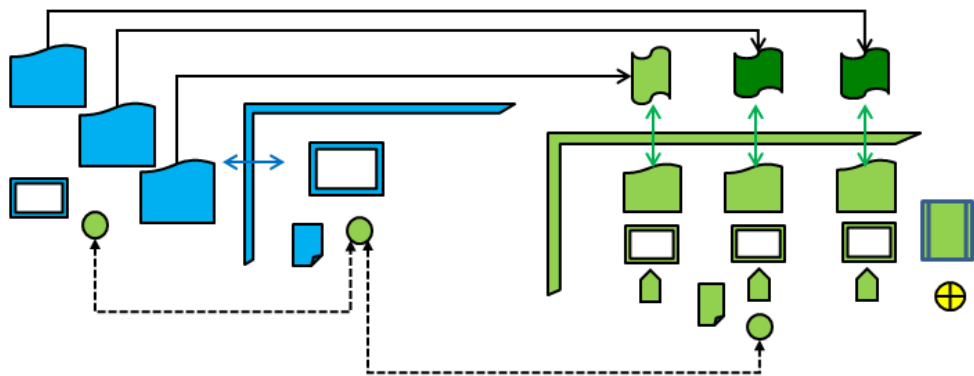
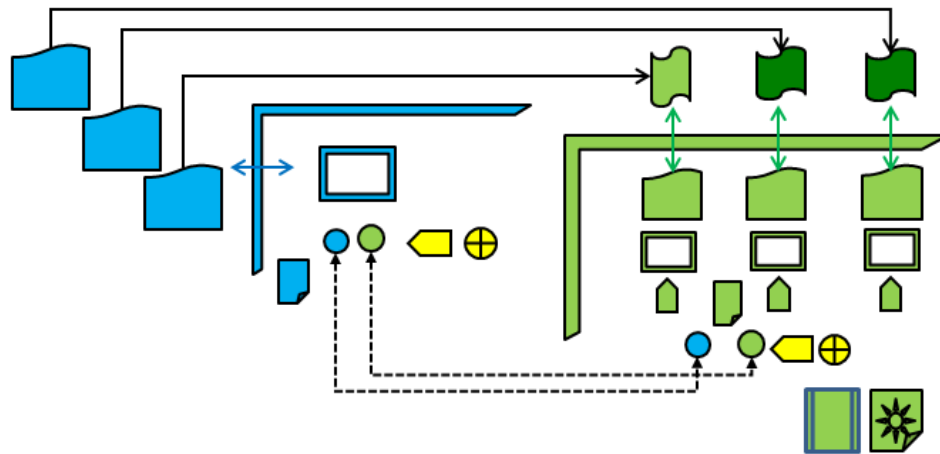


Figure S5. Cont.

Category IV (distributed simulator set-ups)

Configuration 19



Configuration 20

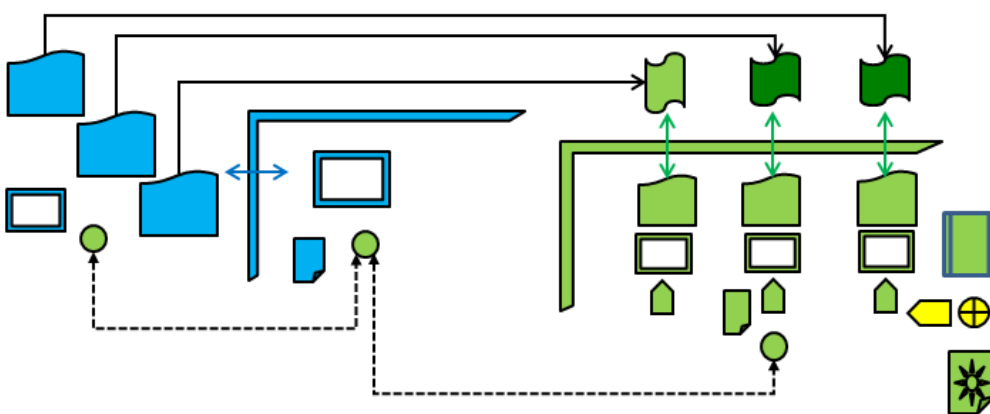


Figure S5. Extended collection of OTS configuration alternatives (twenty permutations shown). In configuration 1–5 (Category I) all training takes place in the control room of the plant: Configuration 1: A basic set-up showing the real plant elements (blue), the control room with control screen, operator and real SOP protocol (blue), the OTS screen connected to the plant model and OTS software, the trainee operator, SOP and training manual (green), the tutor (yellow). Configuration 2: An un-supervised set-up where the control room been extended with several screens. OTS model is provided with an accelerator function to reduce training time. Configuration 3: A set-up where the trainee is supported by an experienced operator. Configuration 4: A set-up where the tutor act during the training as advised by the plant manager. Configuration 5: A set-up where additional OTS screens are used to accurately mimic the control room screen architecture. In configuration 6–10 (Category II) training takes place partly in the plant hall. Configuration 6: Trainee is in the control room in front of OTS placed adjacent to a trained operator running the plant over the plant operation system. The trainee joins the operator into the plant hall. The trainee uses the OTS unsupervised but supported by the SOP. Configuration 7: As in configuration 6 but the trainee is supervised by a trainer that interact with the software settings. The trainer adds incidents for the trainee to act upon. Configuration 8: As in configuration 7 but the trainee is supervised by a trainer that interact with the software settings. Configuration 9: As in 6 where

sampling is carried out from the real plant by experienced operator and where the trainer adds this to the OTS for the trainee to act on. Configuration 10: Real incident occurs in real process and trainer reproduces this in the OTS interface for the trainee to act upon. In configuration 11–15 (Category III) training is carried out in a room aside the control room and the plant. Configuration 11: Level of details in OTS displays. Configuration 12: Accuracy and fidelity of plant models. Configuration 13: Advance training with more models. Configuration 14: Alert messages displayed for operator actions. Configuration 15: One than one OTS display to comply better with the real control site. In configuration 16–20 (Category IV) distributed simulator set-ups are configured from existing software programmes with extended modelling and simulation capacity for selected parts of the plant. Configuration 16: Independent unsupervised training in plant hall. Configuration 17: Actuators represented in OTS display for mimic for actions in plant hall. Configuration 18: Sampling action by operator mimicking real sampling action in plant hall. Configuration 19: OTS set-up allowing experienced operators to test and rehearse incidents. Configuration 20: Manipulating meter values in OTS displays for training of operation actions.

Table S1. Second tier of training needs of plant operators (detailing Table 1 with 1st tier needs).

Need category/need	Target
<i>Training objectives</i>	–
Shorter training period of new-employed operators	Training period is reduced by half
Reduced faulty actions	Faults are reduced by half
Shorter time to independence	New operator can work alone after 4 months
Repetition training possible	The acquired training shall be maintained
Advanced training for more experienced operators	The experienced operators shall meet increasing challenges that further improve operator skill
Improved understanding of the plant	A good understanding of the interdependences of flow and transformations
Training manual interaction with plant hardware	The direct interaction with valves out in the plant shall be trained virtually
Training sampling and actions from these	The operator shall become fully aware of when manual sampling/analysis is required
<i>Technical features of OTS</i>	–
OTS interfaces shall comply to real control system interfaces	The 70%-100% of the process flow charts on the plant's own control shall be included
<ul style="list-style-type: none"> ● Plant section milling compliance ● Plant section liquefaction compliance ● Plant section saccharification compliance ● Plant section fermentation compliance ● Plant section centrifugation compliance ● Plant section distillation compliance 	<ul style="list-style-type: none"> ● 80% compliance (a general understanding is required) ● 100% compliance ● 100% compliance ● 100% compliance ● 100% compliance ● 70% compliance (a general understanding and ability to action on common tasks)
OTS shall deliver messages to the trainee	Pop-up messages of events or change of values on OTS interface shall alert trainee realistically
Allowing training of standard procedures	The standard procedure for regular operation of the plant shall be included of the OTS
Allowing training of incidences	Up to ten common deviations and corrective actions shall be included in the OTS
<ul style="list-style-type: none"> ● Operator shall be able to shut down and start up separate sections of the plant ● Valve and meters to be adjusted at the plant floor included in OTS interface ● Off-line process analytical data shall be presented on the OTS that require operator actions ● Overflow of product tank shall be simulated ● Infection should be simulated ● On-line data on distillation temperature deviates 	<ul style="list-style-type: none"> ● Training shall include key actuators (valve, meter settings) in the plant hall to be represented in the OTS graphical interface ● The interface of the OTS shall expose images of valves in the plant that the operator shall adjust ● The data shall include pH, dry weight and dextrose/glucose from typical measurement points in the process ● Ethanol tank flooding ● Lactic acid bacteria (air born) infects fermentor or liquefaction tank ● Shall allow flow and heat adjustment
OTS shall be available for own use by operator	The operator shall be able to access and start up the OTS independently
OTS shall be possible to run in accelerated mode	The run time of the OTS shall be possible to accelerate up to 50 faster than real-time
<i>Management of OTS</i>	–
Plant manager/Chief operator shall be able to handle and supervise the OTS training	The plant management shall be able to monitor the trainees actions and adjust level of training
OTS software shall be adaptable and easy to update	The OTS shall be provided with update procedures that the plant engineers can maintain
Cost for OTS shall be modest	Investment shall not exceed other similar software
The OTS shall have equivalent hardware displays as the real control room	At least two virtual sections of the plant shall be shown in parallel
Standard PCs shall be able to run the software	The computer hardware needed for the OTS shall require additional / items/ communication cards

Table S2. Second tier of training needs of plant operators (Set 1—all needs are prioritized equally)

Need category/need	Configuration alternatives *																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
<i>Training objectives</i>	-																			
Shorter training of new-employed operators	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Reduced faulty actions	0	0	0	0	3	0	0	3	0	3	0	0	3	0	3	0	0	0	3	3
Shorter time to independence	2	3	2	2	2	3	2	2	2	2	3	2	3	3	2	1	1	1	1	1
Repetition training possible	0	3	0	0	0	3	0	0	0	0	3	0	3	3	0	0	0	0	0	0
Advanced training for more experienced operators	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
Improved understanding of the plant	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Training manual interaction with plant hardware	0	0	0	0	0	3	3	3	3	3	0	0	0	0	0	0	0	3	0	3
Training sampling and actions from these	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
<i>Technical features of OTS</i>	-																			
OTS interfaces very similar to control interfaces	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
OTS shall deliver messages to the trainee	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Allowing training of standard procedures	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Allowing training of incidences	0	0	0	0	3	0	0	0	0	3	0	0	0	0	0	0	0	0	3	3
Valve and meters to be adjusted at the plant floor	0	0	0	0	0	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0
OTS shall be available for own use by operator	0	3	0	0	0	3	0	0	0	3	0	3	3	0	0	0	0	0	0	0
OTS shall be possible to run in accelerated mode	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1
<i>Management of OTS</i>	-																			
Plant manager shall handle OTS training	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OTS shall be adaptable and easy to update	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1
Cost for OTS shall be modest	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1
Standard PCs shall be able to run the software	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2
Total score **:	26	33	26	29	34	39	32	35	35	42	30	29	36	30	29	19	19	22	25	29
Rank	-	-	-	-	-	2	-	4	4	1	-	-	3	-	-	-	-	-	-	-

*) 0 = no effect; 1 = small effect, 2 = middle effect, 3 = high effect; **) weight = 1 for all needs

Table S3. Second tier of training needs of plant operators (Set 2—cost needs are prioritized in the assessment).

Need category/need	Configuration alternatives *																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
<i>Training objectives</i>	-																			
Shorter training of new-employed operators **	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Reduced faulty actions **	0	0	0	0	9	0	0	9	0	9	0	0	9	0	9	0	0	0	9	9
Shorter time to independence **	4	9	4	4	4	9	4	4	4	4	9	4	9	9	4	2	2	2	2	2
Repetitive training possible **	0	9	0	0	0	9	0	0	0	0	9	0	9	9	0	0	0	0	0	0
Advanced training for more experienced operators **	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	9	9	9	9	9
Improved understanding of the plant **	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Training manual interaction with plant hardware **	0	0	0	0	0	9	9	9	9	9	0	0	0	0	0	0	0	9	0	9
Training sampling and actions from these **	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0
<i>Technical features of OTS</i>	-																			
OTS interfaces very similar to control interfaces	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
OTS shall deliver messages to the trainee	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Allowing training of standard procedures	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Allowing training of incidences	0	0	0	0	3	0	0	0	0	3	0	0	0	0	0	0	0	0	3	3
Valve and meters to be adjusted at the plant floor	0	0	0	0	0	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0
OTS shall be available for own use by operator	0	3	0	0	0	3	0	0	0	3	0	3	3	0	0	0	0	0	0	0
OTS shall be possible to run in accelerated mode	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1
<i>Management of OTS</i>	-																			
Plant manager shall handle OTS training **	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OTS shall be adaptable and easy to update **	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1
Cost for OTS shall be modest **	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1
Standard PCs shall be able to run the software **	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2
Total score **: 	42	59	42	55	56	71	54	64	63	72	56	45	68	56	51	38	38	47	50	59
Rank	-	-	-	-	-	2	-	4	-	1	-	-	3	-	-	-	-	-	-	-

*) 0 = no effect; 1 = small effect, 2 = middle effect, 3 = high effect; **) weight = 3 (for all other needs 1)

Table S4. Second tier of training needs of plant operators (Set 3—training needs are prioritized in the assessment).

Need category/need	Configuration alternatives *																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Training objectives	-																			
Shorter training of new-employed operators	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Reduced faulty actions	0	0	0	0	3	0	0	3	0	3	0	0	3	0	3	0	0	0	3	3
Shorter time to independence	2	3	2	2	2	3	2	2	2	2	3	2	3	3	2	1	1	1	1	1
Repetition training possible	0	3	0	0	0	3	0	0	0	0	3	0	3	3	0	0	0	0	0	0
Advanced training for more experienced operators	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
Improved understanding of the plant	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Training manual interaction with plant hardware	0	0	0	0	0	3	3	3	3	3	0	0	0	0	0	0	0	3	0	3
Training sampling and actions from these	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
Technical features of OTS	-																			
OTS interfaces very similar to control interfaces	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
OTS shall deliver messages to the trainee	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Allowing training of standard procedures	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Allowing training of incidences	0	0	0	0	3	0	0	0	0	3	0	0	0	0	0	0	0	0	3	3
Valve and meters to be adjusted at the plant floor	0	0	0	0	0	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0
OTS shall be available for own use by operator	0	3	0	0	0	3	0	0	0	3	0	3	3	0	0	0	0	0	0	0
OTS shall be possible to run in accelerated mode	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1
Management of OTS	-																			
Plant manager shall handle OTS training **	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OTS shall be adaptable and easy to update **	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	2	2	2	2	2
Cost for OTS shall be modest **	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	2	2	2	2	2
Standard PCs shall be able to run the software **	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	4	4	4	4	4
Total score **::	35	42	35	38	43	48	41	44	44	53	39	38	45	39	38	23	23	26	29	33
Rank	-	-	-	-	-	2	-	4	4	1	-	-	3	-	-	-	-	-	-	-

*) 0 = no effect; 1 = small effect, 2 = middle effect, 3 = high effect; **) weight = 2 (for all other needs 1)